The Interaction Between Site, Harvest Residue Management And Plant Stock Quality On *Eucalyptus* Transplant Survival, Growth And Uniformity In Kwazulu-Natal, South Africa

By: G. D. da Costa Alpoim

Dissertation presented for the degree of
Doctor of Philosophy (Forestry)
At the
University of Stellenbosch

Promoter: Professor Ben du Toit
Faculty of AgriSciences
Department of Forest and Wood Science

Co-promoter: Professor Keith Little
Faculty of Forestry
Nelson Mandela University

March 2021

DECLARATION

I declare that the research reported in this thesis, submitted for the degree of Doctor of Philosophy at the University of Stellenbosch, is the result of my own original research, except where otherwise indicated. This thesis has not been submitted for any degree or examination at any other university.

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_ Giordano Diamantino Da Costa Alpoim

March 2021

ABSTRACT

Most eucalypt plantations are managed for short rotations (6 to 8 years) and established across regions with varying water and nutritional stresses. The design and implementation of silvicultural management techniques should be adapted to the specific production and protection objectives, which are strongly governed local edapho-climatic conditions, water resources management, and protection against soil erosion, diseases, pests, bushfires, strong winds and alien species (Goncalves *et a*l., 2017). Although a number of studies have reviewed factors such as planting stock quality and harvest residue management, and their interactive responses, few have quantified the interaction over different sites and the effect on early survival, growth and uniformity through to full rotation. Documented work, specifically in South Africa, focusing on the interaction of mulch residue and differing planting stock of different plug cavity volumes is scarce. Costa *et al*. (2004); Guarnaschelli *et al*. (2003) and Guarnaschelli *et al*. (2006) all confirm that eucalypt seedlings exposed to water stress preconditioning, do experience morphological adjustments whereby total biomass, leaf area and shoot:root biomass ratio, as well as certain physiological dynamics, can be associated with drought hardening.

A combination of substandard nursery plant quality and inconsistent planting practices have been associated with poor survival and sub-optimal growth in eucalypt pulpwood plantations of South Africa and attributed to morphological differences found within plant stock. Plantation forestry is entirely sustainable under conditions of good husbandry, but only where wasteful and damaging practices are avoided. Our understanding of the mechanisms underpinning growth response to harvest residue mulching in hardwood eucalypt plantations remain limited. Forest residue retention is well understood to be an important tool in the sustainability of production forestry; however, it is but one component of a number that are just as critically important. Gonçalves *et al*. (2008) and Stape *et al*. (2002) report that under water and nutritional stress, residues retained on certain sites can increase nutrient availability. This is strongly associated with reduced nutrient and organic matter losses, and the maintenance of important soil physical properties such as porosity, permeability, infiltration and aeration. Du Toit (2003) reports that plantation management operations carried out during the inter-rotational period (harvesting, residue management and certain silviculture operations) have a major impact on the productivity and long-term sustainability of forest stands, especially where short rotations are applied. Retaining residues following harvesting is thus an important strategy for sustaining the productivity of subsequent rotations; however the threat of fire on sites where residues have are retained can be catastrophic with financial losses running into millions of Rands.

Four field trials were planted in the Midlands of KwaZulu-Natal Province, South Africa, to understand the interaction of residue treatments, plant stock size, nursery conditioning protocols and the application of insecticides on survival, growth and uniformity of *E.dunnii* (seedling) and *E.gxn (clone)*, up to clearfell age. It was hypothesised that a combination of mulching, combined with the planting of larger, more robust plants, would ultimately result in better stocked and more vigorously growing out-plantings, with the goal of maximising utilisable timber availability at the end of the rotation. Although burning is a valuable and viable residue management tool, efforts to augment with alternative residue management techniques that are just as productive and beneficial in terms of long-term site sustainability are essential. There is a management aversion to harvest residue mulching due to the high cost; however, experience has shown that there are benefits to be garnered, with fire protection being a potentially strong additional point. The environmental benefits of this technology are promising and the potential gains measurable in the long term. With ever shrinking plantable areas, the environmental and legal pressures placed on obtaining water permits and the growing impacts of climate change, understanding the drivers of early survival, growth and uniformity at the commercial scale are the cornerstone to our business survival. Trial results from this research endorsed the importance of plant quality but this factor can never be viewed in isolation when examining long-term field performance, as nursey plant size, residue management and insecticide applications are all equally important silvicultural inputs, specifically in their early interactions up to canopy closure.

Main effects of the treatments tested that were strongly significant at final rotation, included site, in terms of explaining differences in mean annual increment (MAI), stocking (Spha) and height. Furthermore, stocking was significantly different among residue management treatments. The application of insecticide (main effect) explained significant differences in stocking but mean annual increment did not differ significantly among the insecticide treatments. The best performing treatments across all sites included a combination of a large transplant root plug volume (105 cm^3), planted on slash spread treatment (MAI = 24.8 m^3 ha^{-1}), whilst the worst performing was a standard plug (60 cm^3) planted on a burn treatment (MAI = 22.6 m^3 ha^{-1}).

Relative differences in mean basal area (BA) between burning and mulch, showed initial gains up to 3 years, but this dissipated to zero by full rotation. Transplant root plug volume revealed early gains up to at 3 months but this declined to zero by full rotation. Increases in BA were more specific at the individual trial level, with early plug volume response (1 to 3 years) driven by genotype, but disappeared at full rotation. Small relative gains accrued by not applying nursery hardening up to 1 year, but thereafter were negligible for the duration

of the trial. In summary, relative differences between treatments all showed promising early gains in basal area growth from 3 months, but these all declined to around zero by 4 years and thereafter remained constant through to full rotation.

The results from this study showed that silviculture factors such as transplant plug volume, residue management, nursery hardening and insecticide application, all applied simultaneously at planting, were most responsive (statistically significant differences in basal area growth) from planting to approximately 3.5 years. Thereafter, their individual and combined effects became increasingly difficult to explain or isolate as either main effects or interactions with the additive response of three to four interacting silviculture treatments only able to explain less than 15% of variability after canopy closure, even where significant difference exist. This result was in agreement with several of the key references cited in this study.

Nursery plants raised in large volume cavities (105 cm^3) did not require hardening in the nursery whereas the standard plug volume (60 cm^3) benefited from a gradual reduction in irrigation. Positive gains from 1 to 3 years for root plug volume, residue management, insecticide application and hardening lost significance with time to form only part of an interaction as site effects and intraspecific competition became more dominant.

Stocking and MAI showed very different responses to silvicultural treatments, but for explainable reasons. Stocking proved highly responsive to early silvicultural treatments, and less so to site. A plausible reason for this observation is that mean water deficits were moderate (<100 mm y^{-1} on average) across all site types tested and stocking differences were more affected by silvicultural inputs, either main or interactive effects, over the full rotation. However, basal area growth and MAI, although initially highly influenced by both silviculture inputs and edapho-climatic factors, became increasingly more responsive to the effects of water deficits and nutrient capital driven by intraspecific competition with age.

DEDICATION

To the Heavenly Father who grants us the ability to grow and prosper in life, I give all my gratitude. "*I lift my eyes to the hills. From where does my help come? My help comes from the LORD, who made heaven and earth"* (Psalm 121: 1 - 2).

This research is dedicated to the greatest blessing of my life, my daughter Madison Grace. No greater gift could a Father receive. My hope for you is to follow a life filled with scientific endeavour. To my Mother, Noelle Da Costa, the sacrifices you made in life are not in vain. You inspired and filled me with an understanding that nothing worthwhile comes without hard work.

In closing, the words of Patience Strong have been an inspiration when this project became my very nemesis and climbing the hill turned to staring at the proverbial Mount Everest: *"Things look difficult and dire - if no dream spurs, and no desire – prods you on to scale the crags – when faith grows faint and will power flags.*
What do you wish for all the time? Press on, work hard, prepare to climb – the stairway of the rocky slopes – that wind round the mountain of your hopes…The summits that frown where the cloud veils drop –smile on the man who can reach the top" (Patience Strong (1980).

ACKNOWLEDGEMENTS

A number of people provided invaluable assistance towards the completion of this study. I will mention a few but to those not specifically thanked, I acknowledge your contribution and remain indebted to you.

My gratitude goes to Mondi SA for allowing me to undertake the study and for all of the considerable financial and logistical support. A special vote of thanks goes to the Training and Development Manager, Mrs Kerry Davies for approving the financial support and the additional study leave that you so kindly organised.

I was very privileged to have two excellent scientists as promoters, Professors Ben Du Toit and Keith Little. To Professor Ben Du Toit for your long-suffering patience and vision. I value your vast scientific knowledge, wisdom and guidance, and your professional support was the cornerstone of this study. Thank you for your enthusiasm, critical approach and clarity of thought. Without this, the project would have failed. Every meeting with you always provided me with pearls of scientific knowledge that forced me to think beyond the scope of my study. I am just sorry that we did not conquer the process modelling option, but that was a 'bridge too far' and maybe one day!

I am eternally indebted to Professor Keith Little, Nelson Mandela University, as my co-promoter. Any postgraduate student privileged to have your support and input will find themselves challenged by your high work ethic, but inevitably reap the rewards. Your critical input and rigour to the field trial statistical analysis was invaluable and the results section of this thesis totally hinged on your superb biometrical knowledge. I do also appreciate your regular phone calls of encouragement.

Mr. Shadrack Mokoena, Mr Charles Swart and Mrs. Tracy Newmarch for all of the assistance with the establishment and measuring of the field and pot trials. Your efforts were most important. Finally, to Maurice Chauke, for the statistical analysis of some data sets, thank you and the very best wishes with your PhD study.

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BA	Basal area
C	Control
CCI	Chlorophyll content index
CEC	Soil electrical conductivity
DM	Dry matter
DQI	Dickson quality index
ea	Actual vapour pressure
es	Vapour pressure
L	Large
LAI	Leaf area index
MS	Mean Squares
R^2	R-squared
RCD	Root collar diameter
RGP	Root growth potential
RGR	Relative growth rate
RH	Relative humidity
RWC	Relative water content
S	Standard
SLA	Specific leaf area
SWC	Soil water content
VPD	Vapour pressure deficit
WD	Water deficit
WUE	Water use efficiency

CHAPTER 1

1.0. GENERAL INTRODUCTION AND STUDY OBJECTIVES

Worldwide, various eucalypts are grown commercially and provide a significant contribution towards the world's production of timber (FAO 2000; Ball *et al.* 2007). Regeneration of felled eucalypt plantations in South Africa rely on either replanting (seedlings or clonal material), or the management of stump sprouts (coppice shoots). A study by Thomas (2009) on the coastal region of northern NSW, Australia, showed that although *Eucalyptus pilularis* Sm. has desirable growth and superior wood properties, high seedling mortality shortly after planting remained a major concern hindering successful establishment. In line with the South African practice of planting during summer, plantations in NSW Australia are established during the months of highest rainfall. Thomas (2009) reports that the death of *E. pilularis* by 'transplant shock' is typically associated with dehydration following planting and generally occurs 2 to 4 weeks post planting. It is thus reasonable to assume that mortality can be greatly reduced by ensuring that planting stock are adequately and continuously watered during this most susceptible period. Burdett (1990) states that the survival of containerized transplants is dependent on the ability to rapidly generate new roots and access surrounding soil for sufficient moisture if they are to meet their evapo-transpiration demand. If the plant does not receive water during the period of root regeneration, its internal water deficit will increase with concomitant potential for vascular collapse.

Intensive forest management hinges on the manipulation of site resources, genetics and stand structure to exploit fully tree growth. Intensive silviculture practices are most effective when there is a balance between mitigating the limitations on productivity, maximizing allocation of production to harvestable fibre, providing economic return and sustaining site productivity (Vance *et al*., 2010). Whyte *et al*. (2016) state that global industrial plantations have expanded by almost 20% in the last 20 years to close on 109 million hectares, and projected to double in the next 40 years. Eucalypts are the most widely planted hardwood species with plantations established in over 90 countries (Booth, 2013), over 20 million hectares. Forrester *et al.* (2010) report *Eucalyptus* plantations worldwide have increased significantly over the last two decades and covered approximately 19.0 million hectares just 3 years earlier.

Of the 894 *Eucalyptus* taxa, nine species and their hybrids account for more than 95% of plantings (Whyte *et al*. (2016). Plantations are generally even aged monocultures selected for their fast growing properties and managed to optimise primary productivity by controlling

biotic and abiotic stressors that limit growth and quality (Barry and Pinkard, 2013, Whyte *et al.,* 2016). They are generally grown outside their natural range and hence vulnerable to stress (Whyte *et al*., 2016) but the ever-increasing demand for wood to reduce pressure on harvesting native timber, their rapid growth rates, superior wood properties, and more recently, carbon sequestration capabilities make them highly desirable.

As of 2015, South Africa had 1,224 million ha planted to timber, 86% privately owned and 14%, under state control (Forestry, South Africa, 2017). There is little opportunity for expansion and in reality, the planted area has shrunk due to limited suitable new sites and strict water licensing regulations. South African forestry is challenged by difficult establishment conditions and foresters are continuously pressurised to ensure the highest possible survival, growth and uniformity. Even with the greatest care and attention, 100% survival has been more an exception, especially in industrial plantations with extensive re-establishment programmes. In comparison, Brazil possessed 7.2 million ha of timber plantation (IBA, 2014), with significant potential for major expansion still available. Gonçalves *et al.* (2008) indicate that in 2005, Brazil established 553 000 ha of new area to timber, of which 422 000 ha, or 76% was planted by corporate forestry companies. Of this total, 130 000 ha were planted under a forest incentive program. Gonçalves *et al*. (2008) report that since 2010, it has been the goal of the Brazilian National Forest Program (NFP) to annually plant 1.0 million hectares of new plantations. This incentive is a joint private and public initiative to contribute to the socio-economic development of timber production in Brazil.

This massive Brazilian afforestation programme over the last 30 years has been accompanied by substantial investments in research and technology, resulting in the mean productivity of *Eucalyptus* plantings increasing from 10 m^3 ha^{-1} yr^{-1} (1965) to the current 38 m^3 ha^{-1} yr^{-1}, with the best Brazilian sites, yielding 45 – 50 m^3 ha^{-1} yr^{-1} (Gonçalves *et al*., 2008). Unfortunately, South Africa has no such initiative to drive the growth of the local forest industry; quite the contrary, the restrictive nature of legislation (Section 21d – National Water Act 36, 1998) has resulted in an industry that has decreased in planted area. For the local industry to incur moderate volume gains, or at least retain current yields, in an environment plagued by marginal sites and water deficits will be very challenging, especially in the light of increasing signs of climate change becoming a sobering reality.

Clark *et al*. (2003) and Whitmore *et al*. (2009) state that irrespective of the drought resistance of the species, dry soils impose serious physical limitations on root growth that affect water absorption and exploration by lateral and fine roots.

South African forestry sites unfortunately undergo prolonged dry periods that place immense stress on resultant net primary production. Morris *et al*., (2004), Whitehead and Beadle (2004) raised a concern over the water use by *Eucalyptus* plantations worldwide and the possibility for conflict when processes are not fully understood. Forrester *et al.* (2010) warn that enhanced productivity can be associated with increased water use and it is not clear if this is proportional to productivity increases or changes in water use efficiency (WUE). However, any improvement in WUE is highly desirable to reduce the global demand for water and the economic and environmental expense of producing and applying fertiliser. Ovalle *et al*. (2015) predict that climate change, with reduced or uneven rainfall events, will create even drier soil conditions and impose greater stress on root growth. Padilla *et al.* (2015), Hertel *et al.* (2013) state that roots can respond to reduced rainfall or water shortages by producing longer roots and increasing the productivity of fine roots to allocate more biomass to the root system. Giliberto and Estay (1978) report that water availability has a positive impact on root collar diameter and shoot growth of species with shallow root architecture but shoot growth is significantly reduced.

Guehl *et al*. (1993) note that disturbance at the soil-root interface and mechanical damage caused by transplanting of tree seedlings (bare root or containerized) are accompanied by transplant stress, which inevitably leads to plant mortality or reduced growth. This transplanting stress involves a series of physiological and metabolic disorders that reduce a plant's ability to regenerate and elongate new roots after establishment. Changes in plant water status and water relations are major factors contributing to transplanting stress. Ovalle *et al*., (2015) reports that summer drought in the Mediterranean ecosystems seriously affect tree survival with mortality up to 70% in the first post-plant season.

Royo *et al*. (2003) report a number of causes for failure of forest tree plantations. Genetic factors, nursery cultivation techniques and the environment at the plantation site can affect planting stock. Often, even when using the same seed source planted on similar sites, field performance can be different, reflecting differences in factors collectively referred to as seedling quality. Giliberto and Estay (1978), in an early publication, state that shallow rooting and less drought tolerant trees show different survival rates depending on the availability of water with the difference in survival rates most pronounced by the end of the second growing season, even with the onset of the rainy season.

Early crop survival has serious economic consequences for any forestry company, as the potential utilisable volume will be reduced significantly. Thomas (2009) reports that although timber plantations have become increasingly important to ensure sustainable wood

supplies, a major cost inhibitor is the expense incurred at establishment. Part of these costs consist of producing and planting seedlings, but if initial plant mortality is high, then additional expenditure on replanting becomes necessary. A reduction in plant mortality associated with poor establishment conditions post-planting, must strive to increase the economic viability of plantation forestry. However, it is likely that the costs and benefits of such operational interventions will differ with species, site quality and timing of re-establishment (Thomas, 2009). Ovalle *et al*. (2015) report that as roots are so sensitive to small changes in soil moisture, plant mortality rates increase exponentially with a decrease in rainfall and hence watering is essential to encourage root growth and survival. León *et al*. (2011), Benayas *et al*. (2004), Valdecantos *et al*. (2014) recommend water supplementation in the first year after planting as this has beneficial effects on the morpho-functional traits of species with differing rooting strategies and inevitably sapling survival.

This study focused on the utilisation of two widely planted genotypes in South Africa, *E. dunnii* seedlings, a species that dominates the re-establishment of cooler and drier sites and an *E. grandis* x *E. nitens* (*E. gxn*) hybrid clone planted on deeper, more apedal soils of the higher rainfall parts of the eastern seaboard, at altitudes in excess of 1000 m. Additional reasons for these two genotypes choices, propagated by different nursery methods, was root morphology, their abilities to resist pest and diseases and suitability to the pulp market. Gonçalves *et al*. (2008) and Souza (2002) report that *Eucalyptus* (including *E.gxn*) propagated from macro-cuttings have a root system comprising a non-pivoting root with several thick secondary roots. Clonal plants appear to lack the ability to penetrate harder soils as pivoting roots typical of seed propagated stands are able to do. In contrast, Ovalle *et al*. (2015) report that drought tolerant Mediterranean trees are able to rapidly increase soil exploration capacity to zones where moisture levels exist by re-allocating resources to root growth at planting. Rapid and deep root development is a very important trait for early survival where prolonged dry conditions prevail or rainfall is erratic. Ovalle *et al*. (2015) add that small secondary roots, long root length and high adsorptive root surfaces are important factors in the ability to maintain a high and stable xylem water potential (Ψ) and hence rooting habits and root plasticity are two core functional components during periods of drought.

Forest companies continue to focus efforts and resources to re-establish productive sites to hybrid clones, whilst marginal sites limited by shallow rooting depth are planted to *E. dunnii and E. benthamii*. This centres on optimising volume growth and attaining greater pest resistance. Gonçalves *et al*. (2008) note from their Brazilian experience that although there is concern as to the vulnerability of clones, attack by pests does not discriminate

between seed or clonal plantations. Gonçalves *et al*. (2008) report that species influence is a lot more of a determinant than clonal plantings in the increase of plantation vulnerability to insect attack. Conversely, clonal propagation has become a valuable solution to combat pathogenic attack. Although site-species or site-clone matching is of prime importance, Ovalle *et al*. (2015), counter that root morphological studies focusing on dry land reforestation have not adequately considered the different rooting strategies of tree species.

The growing demand for plantation timber, together with a reduction in available land for plantation expansion, has increased the importance of the adoption of sustainable forestry practices (Tutua *et al.,* 2008). The ever-increasing pressure on forestry land and most notably water licensing, necessitates a greater focus than ever on maximising yield per unit area on a sustainable basis. Evans (1999) states that sustainability in plantation forestry has two components, broad-sense and narrow sense. Broad-sense sustainability refers to whether utilising land and devoting resources to tree plantations is sustainable in the economic, environmental or social sense. Narrow sense sustainability determines whether tree growth in plantation form is viable in the long term. More specifically, can productivity be reasonably assured or will it decline over time? Are today's silvicultural management practices more damaging due to the pressure for higher timber yield from the same unit area, over shorter rotations? Furthermore, are genetic improvements, refined fertilizer treatments and more sophisticated manipulation of stand density likely to lead to crop improvement with time, or could they mask evidence of genuine site degradation or increasing risk of damaging pests and diseases? What does this all mean in terms of long-term site resilience?

Benefits of the organic matter layer are in the contribution to 1. Physical, 2. Chemical and 3. Microbial soil health. There are also ecological contributions above the soil. For example: surface protection (water and wind erosion, and temperature stabilisation), replenishment of soil carbon and supply of soil nutrients to the soil biology. Organic matter also contributes to surface carbon and to soil surface flora and fauna. (Evans, 1999). There are human activities or management interventions that can be beneficial or detrimental to the ecosystem and/or the forest plantation. No-burn policies can reduce decomposition rates, increase wildfire risk and reduce N supply to trees (Binkley et al., 2004).

Any activity in a forest that disturbs the role played by the undisturbed litter layer in the ecosystem can have profoundly negative effects. Examples include accumulation where carbon: nitrogen ratios exceed 70:1 will compromise normal decay rates (Adams *et al*., 1986). Conversely, over-zealous burning of harvest debris where large quantities of

nitrogen are volatilized and leaf litter destroyed in a rotation, and the most serious of all, frequent litter raking or gathering of harvest debris. The cost of managing residue and site preparation at replanting is high and represent a large percentage (45 – 56 %) of establishment costs. It is also clear from the literature that the few examples of recorded yield decline mostly relate to damaging practices involving litter and organic matter (Evans, 1999).

The main objective of sustainable timber plantations must be balancing resource supply and replenishment with demand for the life of plantation, while enabling the system to be rehabilitated. To achieve this, management operations should never exceed the natural capacity of sites to reinvigorate themselves. Greater timber yields may be realised through a combination of improved genetic stock, site – species matching and implementation of optimised silvicultural practices (Rolando *et al*. 2002); however, this is a complex process involving a multiplicity of variables, both independent and interdependent. It is possible to follow an ordered flow of processes that if optimised, will lead to a sustainable supply of timber (Figure 1.1). The blocks highlighted in yellow (Figure 1.1) indicate silviculture cultural practices that are integral to this study.

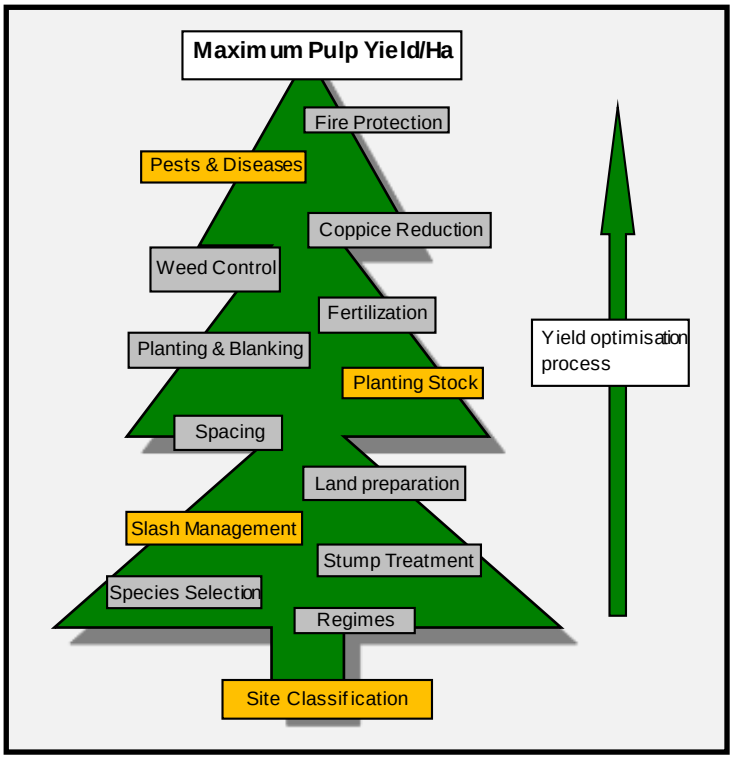

Figure 1.1: Silviculture processes to realize optimum sustainable fibre yield

Focusing solely on site preparation and planting technique is insufficient to explain why plant mortality remains a re-establishment nemesis. Evans and Turnbull (2003) note some very important questions:

1. Will planting of extensive monocultures and subsequent clear felling initiate site change?
2. Are such changes more or less favourable to the next crop?
3. Does growing one crop influence the potential of its successor?

This study attempts to explain certain reasons for persistent transplant mortality, with emphasis on the interaction of i) site, ii) plant stock quality and, iii) residue management (Figure 1.2). Site characteristics focused on the impact of climate and soil form whilst residue management was restricted to three specific treatments; i) residue burning, ii) spreading residues, and iii) residue mulching. Nursery quality focused on plant stock raised in black plastic trays of the same configuration, but differing cavity volume. Binotto *et al.,* 2010) suggest that healthy, robust stock from a larger cavity, survive better across a range of adverse conditions; however, this early response may not be realised in final stand volume

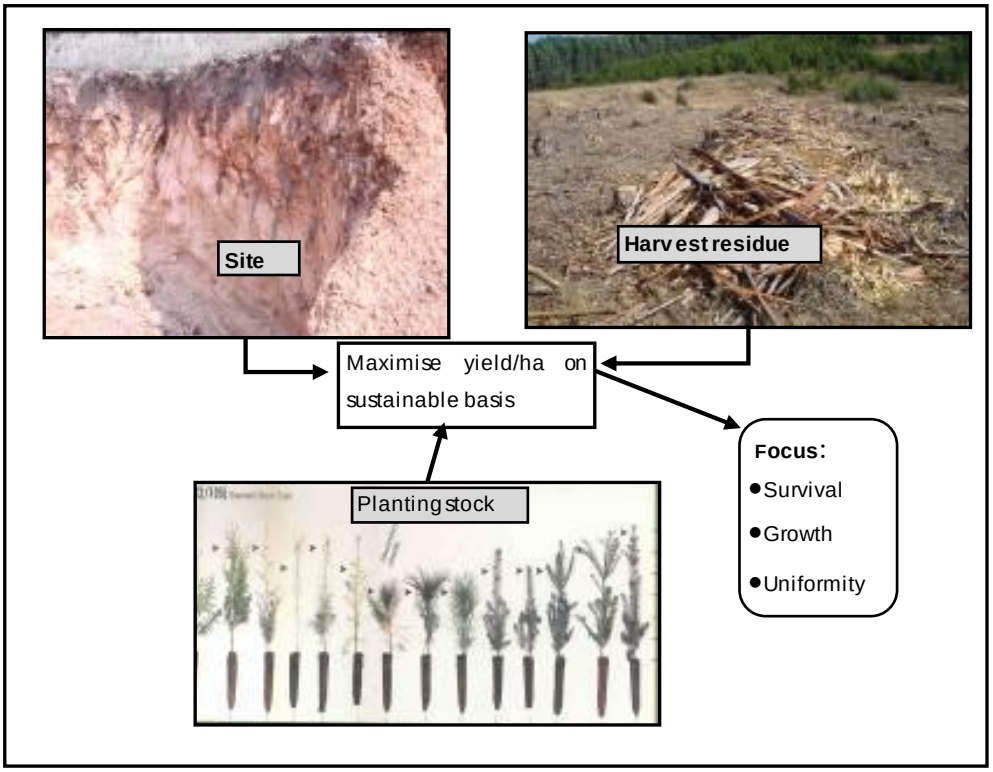

Figure 1.2: The interaction between site, harvest residue treatment and planting stock

1.1. OPERATIONAL SURVIVAL AND UNIFORMITY AT 3 MONTHS

Results emanating from commercial survival and uniformity scores at three months (664 inventoried compartments across 8598 ha – Figure 1.3) showed survival was 95% at 4

weeks after planting and 84% at 13 weeks. This is a serious concern for final stocking and utilizable yield, but also hampers the decision to coppice as this requires 95% surviving stumps at rotation age.

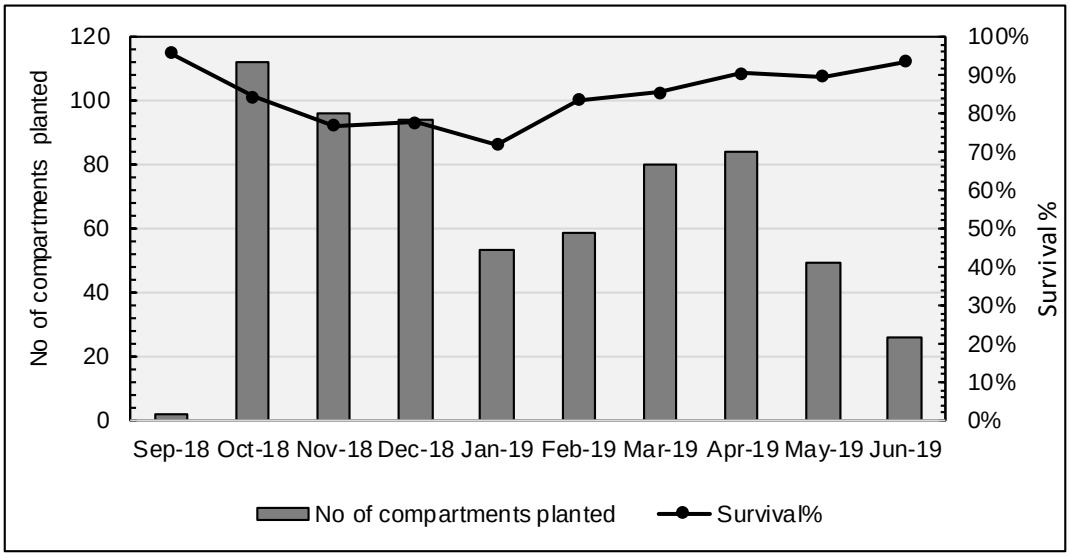

Figure 1.3: Mean survival % from planted compartments (Mondi Planning Dept. October 2019)

Silviculture practices (stocking, pit quality and weeding) scored highly; however, nursery stock quality and planting practices have highlighted significant weaknesses. Of 321 nursery batches sampled, 38% did not meet the internal plant quality criteria. Of concern was erratic tree uniformity scores at three months. Tree uniformity i influences the estimation of tree volume at rotation-end, pulp yield and the efficiency of planning, and execution of harvesting operations (Little 1999). Early uniformity scores, based on the coefficient of variation of height (cm) were low with 56% recorded for clones and 39% for seedlings across sampled compartments.

1.2. SURVIVAL IN SHORT ROTATION PLANTATIONS

Survival and initial growth are associated with a number of silvicultural practices including transplant quality, transplant age, and site species matching. These factors are especially critical when nursery stock is planted under adverse climatic or environmental conditions that undermine plant ability to exploit site resources (Rolando and Little, 2008). Burdett (1990) states that the ability of planting stock to withstand stress is a function of phenology (biological phenomena correlated with climatic conditions), physiology and site factors. Zwolinski and Bayley (2001) add that an integrated establishment system must incorporate the principle components of (i) plant stock, (ii) site and the environment, and (iii) applicable silviculture techniques. Although not a new concept, very few regeneration studies have

attempted to link all three factors into one integrated system and hence this study attempts to offer greater insight into the impact of these interactions. Twelve month assessment data revealed mortality percentages after establishment to be high, with a mean survival of 81% for *E. dunnii* and 86% for *E. gxn* (Table 1.1, Figure 1.4) in the Piet Retief area.

Table 1.1: Twelve month survival of *E. gxn* and *E. dunnii* - Piet Retief, SE Mpumlanga

Genotype	N	Mean %	Median %	Minimum %	Maximum %	Variance	Std. Dev.	Error	Skewness
E.dunnii	18	81.14	83.82	52.00	100.04	173.57	13.17	3.11	-0.68
E.gxn	33	86.13	87.86	52.02	103.9	87.65	9.36	1.63	-1.63

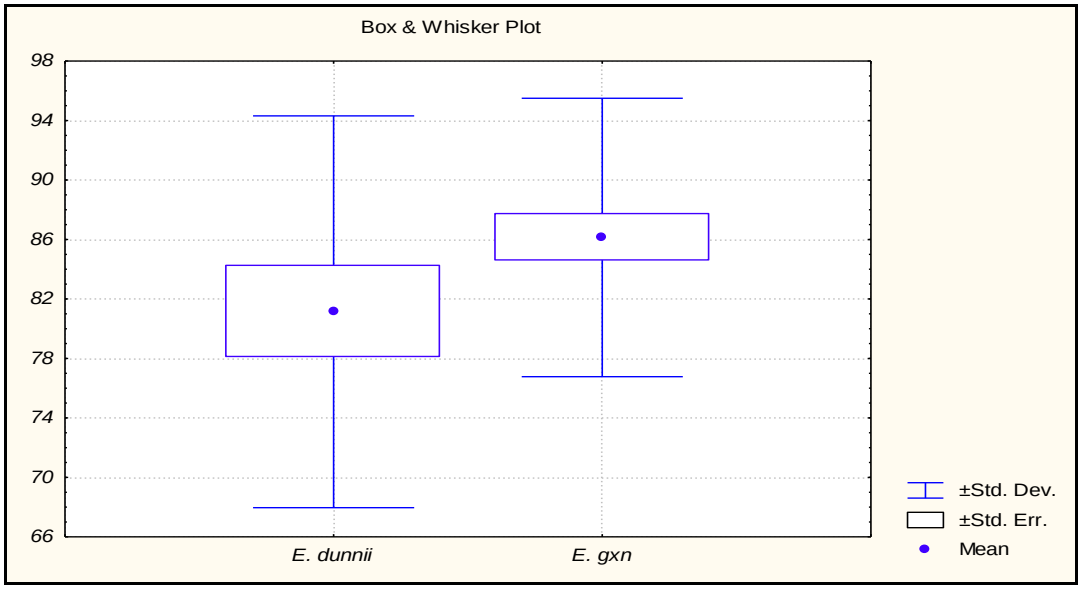

Figure 1.4: Box and whisker plot for 12-month survival data - *E. dunnii* and *E. gxn*

Based on the above findings, four field trials were established in the Midlands, KwaZulu-Natal Province, South Africa, to investigate the interaction of harvest residue treatments, plant stock size, nursery conditioning protocols and the application of insecticides on survival, growth and uniformity of *E.dunnii* (seedling) and *E.gxn* (clone), up to clearfell age. To determine whether significant treatment differences were present, planting occurred from late February to early April, when summer mortality can be triggered by prolonged periods of low rainfall, accompanied by high diurnal temperatures. The null hypothesis stated that no difference in survival, growth and uniformity existed across varying treatments applied to *E.dunnii* and *E. gxn*, to clearfell age. The alternate hypothesis stated that significant variation was expected across treatments, with the best survival, growth and uniformity projected for a combination of mulching, a large (105 cm^3) primed root plug and insecticide (low residual action) applied at establishment date.

The objectives of the study are summarised as follows:

1. Identify factors that cause mortality at establishment due to differences in site, residue management, plant stock (transplant) size and quality for *E. dunnii* and *E. gxn*.
2. Determine whether the application of an insecticide with low residual action would provide improved survival, growth and uniformity, in combination with the treatments stated above (point 1).
3. Gauge differences in resource availability (water and nutrient supply) to young transplants under various residue management practices and quantify the effect on early tree growth.
4. Examine the economic viability of mulching as an operational forestry tool, compared to burning or the retention of harvest residues.
5. Examine the potential of deploying larger, more robust and better-conditioned planting stock.
6. Investigate the relationship between transplant morphological characteristics at planting, environmental stress (predominantly water stress), survival and growth up to clearfell age.
7. Quantify the physiological response (stomatal conductance and chlorophyll content) of *E.dunnii* and *E. gxn* transplants to environmental stress and the effect that three harvest residue treatments, and two nursery cavity sizes may have in moderating or ameliorating water and nutrient stress effects.

CHAPTER 2: LITERATURE REVIEW

2.1. DEFINING STRESS

Biological stress is any change in environmental conditions that adversely change plant growth (normal functions) whilst biological strain is the reduced function. When environmental conditions are such that a plant responds maximally to some factor, no stress exists. Any change in environmental conditions that result in a plant response that is less than the optimum is stressful (Levitt, 1972; Levitt 1980).

Levitt (1972) defined elastic biological strain as those changes in an organism's function that return to the optima when conditions are again optimum (biological stress is removed). If the functions do not return to normal, the organism exhibits plastic biological strain. Plastic strains include frost, high temperature, limited water, or high salt concentrations. Elastic strain includes reduced photosynthesis in response to low light. Levitt (1972), Levitt (1980) further distinguished between avoidance and tolerance (hardiness) to stress factors. In avoidance, the organism responds by reducing the impact of the stress factor. For example, a plant in the desert avoids dry soil by extending its roots down to the water table, by shedding leaves, forming tubers or inducing winter/seasonal dormancy. If the plant develops tolerance by thickening of cell walls in leaves and early stomatal closure, it is able to endure the adverse environment. Ovalle *et al.* (2015) state that deep-rooted and drought tolerant tree species have a high survival rate independent of water availability, indicating a high degree of flexibility to drought conditions.

Larcher (1987) modified the term stress and concluded that a stress factor is equivalent to Levitt's stress and a stress response equals biological strain. Larcher concluded that Levitt's concept works best when dealing with individual stress factors, although more than one stressor typically causes stress responses at a time (Larcher *et al*., 1990). Hot summer weather may induce stress factors of high light levels (photo-destruction of chlorophyll), low humidity, dry soil, and high temperatures. Stress responses are typically complex, exhibited by various parts of the plant, and may involve stress hormones such as abscisic acid (ABA) and ethylene distributed throughout the plant (Larcher, 1987).

2.2. STRESS AND DROUGHT RELATED MORTALITY

In Australia, the resistance of germinants to drought has influenced the evolutionary distribution of *Eucalyptus* species. Responses of *Eucalyptus* to water stress include changes in root/shoot ratio, growth rates of foliage and stems, water use efficiency,

hydraulic conductivity of roots, tissue osmotic potential, diurnal patterns of stomatal conductance, relative water content at stomatal closure, leaf wilting potential at wilting point and changes in transpiration rate or turgor as water stress increases. No relationship between the intensity and duration of water stress and seedling growth has ever been established (Myers and Landsberg, 1989).

Manion (1991) hypothesised a three-stage decline theory resulting in plant death. Initially, a long term stress phase (pre-disposing factors) caused by poor edaphic location, a failure to match the species to the site; followed by a severe short term stressor (inciting factors) such as caused by drought and finally death by a contributing factor such as a pathogen. McDowell *et al.* (2008) developed a hydraulically based theory that considered the carbon balance and insect resistance as central to survival and mortality.

McDowell *et al.* (2008) note that severe droughts are linked to forest mortality and climate change will exacerbate this further. However, the scale and intensity of the effects are difficult to predict, as the physiological mechanisms underpinning drought survival and mortality are not fully understood. Gutschick and BassirRad (2003), Tubersoa *et al.* (2003), Hamrick (2004) report that genetic differences play an important contributory role in these mechanisms but is not necessarily the reason for mortality or survival. However, there is intra-specific genetic variation in drought resistance characteristics such as xylem vulnerability to cavitation; hydraulic conductance; water use efficiency; stoma size and density and insect attack (McDowell *et al.,* 2008). Mitton (1995) states that wind pollinated tree species with a high-expected longevity could be the most resilient for future droughts where genetic factors are critical to survival. McDowell *et al.* (2008) indicate that vegetation mortality most often points to water limitation as the driver. Genetic inheritance of specific drought survival traits plays a major role, but at the landscape level, intraspecific mortality is highest on aspects facing the sun, north and western aspects in South Africa, on well-drained soils or exposed ridge tops. Pederson (1998), Demchik and Sharpe (2000), Lloret *et al.* (2004) have shown that tree mortality only occurs after exposure to prior droughts that initiate a sharp growth decline or in response to prolonged drought. McDowell *et al.* (2008) state that drought appears to kill trees on either end of the size gradient – as seedlings or as tall trees, whilst Pittermann *et al.* (2006) report that conifers maintain a larger margin of safety from hydraulic failure than angiosperms, that improves their survival during drought.

Gonçalves *et al*. (2004) report that plantation productivity is generally lower than their physiological potential as the supply of either light, water or nutrients is less than optimal. This is even more applicable in water scarce countries like South Africa. However,

maximum growth does not also equate to maximum wood value. Gonçalves *et al*. (2004) note that the greatest challenge is a silviculture regime that targets growth rates and wood quality by manipulating the available resource supply and hence it is possible to ameliorate factors limiting growth through soil cultivation, residue management, fertiliser applications, weed control, coppice management, thinning and pruning. Gonçalves *et al*. (2004) state that eucalypt silvicultural practices generally target short rotations and due to their relatively fast growth rates and generally low-nutrient use efficiencies, have a tendency to deplete site nutrients if nutrient conservation is not a management practice. To elucidate a framework to describe mechanisms driving tree mortality, McDowell *et al.* (2008) examined factors such as biotic agent demographics, hydraulic failure, carbon starvation (Figure 2.1) and how these mechanisms relate to the intensity and duration of water stress. All three mechanisms have been shown to operate exclusively or inclusively of one another.

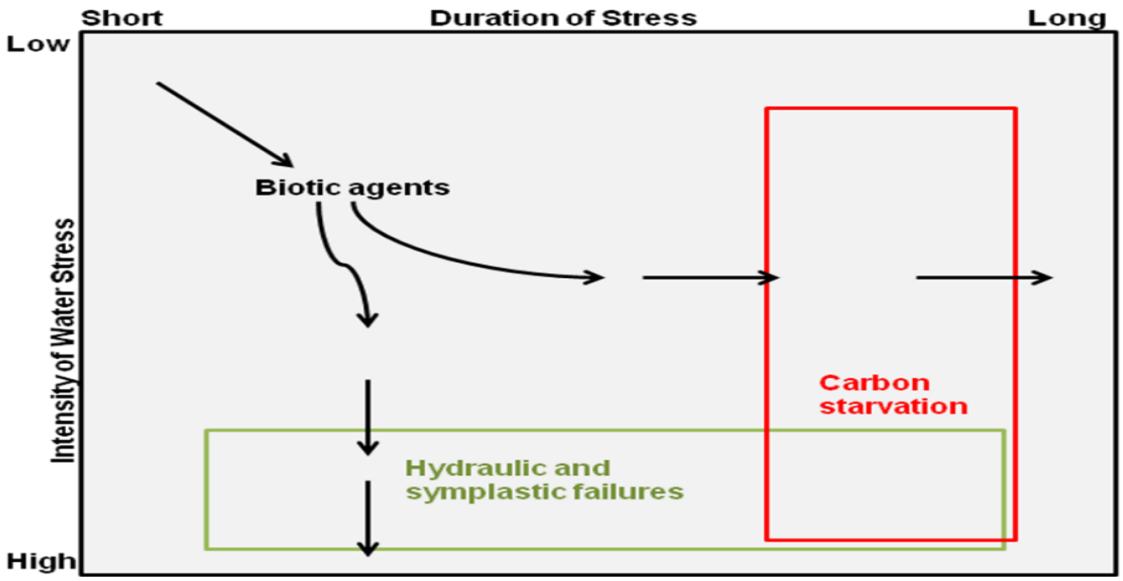

Figure 2.1: Hypothesis of intensity and duration of water stress (McDowell *et al.*, 2008)

2.3. BIOTIC AGENT DEMOGRAPHICS

The biotic agent demographics hypothesis suggests that drought drives change in insect and pathogen population dynamics, synchrony of key developmental phases and geographic range because of warmer winter minimum temperatures, and subsequently tree mortality increases (McDowell *et al.,* 2008). Lloret *et al.* (2004) report that drought related mortality does not always include a biotic agent and hence this hypothesis can only explain a portion of mortality. In turn, Hastings *et al.* (2001), Grosman and Upton (2006), Romme *et al.* (2006) counter that plants treated with insecticide often survive insect outbreaks, inferring that biotic agents play a significant role in mortality. The impact of biotic agents are

amplified by plant physiological stress, resulting in hydraulic failure where beetles inoculate sapwood with xylem occluding fungi that inhibit the translocation of water, or carbon starvation by increasing carbon loss to resin production. Conversely, hydraulic failure or carbon starvation can increase biotic attack where carbon based defence mechanisms, such as resin production and increased release of volatiles, such as ethanol, that attract insects and trigger changes to the food quality for insects (McDowell *et al.,* 2008).

2.4. PLANT-WATER RELATIONS

The hydraulic failure hypothesis predicts that reduced soil water linked to high evapo-transpiration demand causes xylem conduits and rhizosphere (plant-root interface) to cavitate), inhibiting the flow of water and causing desiccation of plant tissue and cell death. Hydraulic failure is most likely if a drought event is intense enough that plants run out of water before they exhaust carbon reserves (McDowell *et al,* 2008). The carbon starvation hypothesis predicts that stomatal closure (to stop hydraulic failure) reduces photosynthetic uptake of carbon, causing the plant to starve due to carbohydrate metabolic demand. The situation is exacerbated by photoinhibition linked to high temperatures during drought. Carbon starvation is hydraulically driven, even when drought does not cause hydraulic failure, but lasts so long, resulting in the exhaustion of plant carbon reserves (McDowell *et al,* 2008). Trees possess an inherent ability to reduce evapotranspiration (*E*) from exceeding critical rates (E_{crit}) which will result in hydraulic and symplastic (inner side of the plasma membrane) failure (Ψ_{crit}). It is imperative to avoid E_{crit}, but if it its avoidance (through partial stomatal closure) endures for a long time, the depletion of carbohydrate reserves will result in carbon starvation (Cowan and Farquhar, 1977; Katul *et al*., 2003). McDowell *et al.* (2008) emphasize that plants must replace water lost through to retain tissue hydration and photosynthesis. The cohesion tension theory states that a tension exists that pulls water from soil, through the plant and to the crown, where it diffuses back to the atmosphere, through a soil-plant-atmosphere hydraulic continuum described by the formula:

$$E = K_1 (\Psi_s - \Psi_l - hp_w g)$$ where:

K_1 = leaf specific hydraulic conductance.

$\Psi_s - \Psi_l$ = soil and leaf water potentials respectively.

$hp_w g$ = gravitational pull on a water column of height *h* and density *pw.*

The tension difference across the plant ($\Psi_s - \Psi_l$) increases in proportion to evapotranspiration (*E*) as long as the leaf hydraulic conductance (K_1) remains constant and no cavitation occurs. This is an efficient system, as no metabolic energy needs to be exploited to drive it. However, *E* has an upper limit, (E_{crit}) as increasing tension causes

decreased leaf hydraulic conductance (K_1) due to air entering through pit pores into conduits, causing cavitation and embolisms or an air-filled conduit. In effect, hydraulic failure occurs in a plant when E exceeds the critical water potential (Ψ) and leaf hydraulic conductance (K_1) equals zero, and the plant can no longer translocate water (McDowell *et al.,* 2008).

2.5. HYDRAULIC FAILURE IN SOIL AND STOMATAL REGULATION

Evans (1999) states that water use by trees is a well-researched subject leading to the conclusion that when compared to grassland and many agricultural crops, trees exhibit higher levels of evapotranspiration. Kozlowski (1972) reports that in the early morning, the turgor of leaf cells of plants in moist soil is usually at its highest. As water is lost during the day through transpiration, moisture deficits at root surfaces increase. Diurnal variations start to occur and soil water deficits at the root surface decrease at night (stomates closed) when water moves to root surfaces. Water deficits again increase during each day of a soil drying cycle and diurnal changes in leaf water deficits occur, with a lower deficit at night than during the day. With further soil drying, diurnal recovery in the water balance in the soil next to the roots, and leaves, occurs less rapidly. Leaf turgor decreases each succeeding day of the soil drying cycle and the water deficit in the plant remains consistently higher than the soil deficit. Finally, turgor pressure in the leaves drops below a critical threshold and reaches a permanently wilted state.

Slayter (1957, 1967) records that permanent wilting is reached when the water potentials of the leaf, root and soil immediately around the roots are equal and turgor pressure is zero; however, Gardner and Ehlig (1965) report physical symptoms of wilting at turgor pressures of 0.2 - 0.3 MPa. Permanent wilting point links to the elastic properties of the cell when turgor pressure drops below a critical value and not necessarily when it reaches zero. At turgor pressures above 0.2 MPa, leaf thickness remains relatively constant but below that the modulus of elasticity decreases markedly and leaves begin to sag. Kozlowski (1972) states that the relationship between turgor pressure and wilting is confounded by supporting tissue found in leaves, *Ilex* and *Pinus sp.,* that are permeated by lignified tissue and do not droop readily, even when parenchyma cells have lost turgidity.

Forrester *et al,* (2010) note that sap flow velocity in eucalypts is related to maximum daily temperature, mean daytime VPD and solar radiation; however, such correlations are strongly related to season. To simplify site-species matching, there is a tendency to rely on empirical mean annual precipitation (MAP) and to a lesser degree, mean annual

temperature (MAT), as the sole climatic factors to consider when establishing timber plantations. Although more complex, a clear understanding of the hydrological balance is critical with Cruff and Thompson (1967) indicating that such a hydrologic balance must express total water loss due to evaporation and transpiration from all surfaces of the growing area. Cruff and Thompson (1967), Van Hylckama (1959), Ward (1975) state that the aim of measuring evapotranspiration is to determine the effectiveness of precipitation; however, potential evapotranspiration (E_p) can be used as a surrogate as it equates to the volume of water that may evaporate from the soil and the amount transpired by plants if soil is moistened throughout. Palmer and Havens (1958) add that the loss of water from the earth to the atmosphere by transpiration from vegetation, and by direct evaporation, constitutes an important part of the water balance problem. A similar calculation, i.e. the water deficit, (Pereira, 2007) also provides a balanced calculation of rainfall, soil water storage and evapotranspiration.

Herbert (1984) concluded from a study over three rotations in Kwa-Zulu Natal, South Africa, that the productivity of each rotation of *Acacia Mearnsii* was determined by summer rainfall and soil moisture reserves, especially on more marginal sites. There is a general tendency to overlook soil moisture reserves, or fail to augment moisture through irrigation to grow tree plantations, but rather match species with the prevailing climatic conditions (Evans, 1999). In wetter, cooler climates such as Western Europe, the common observation is that a site re-wets when a stand is clear-felled. This brings to an end a period of drier soil conditions, which may assist soil aeration, at least for a time until the next crop is established and canopy closure reached. This phenomenon is especially obvious on surface water of soils with gley horizons. The higher levels of evapotranspiration of trees in climates where a moisture deficit is rare may contribute to improving conditions for subsequent regrowth and may explain in part the generally better growth of second-rotation stands as noted in the United Kingdom (Evans, 1999).

Stomatal closure occurs where the water content of subsidiary cells decreases and creates a water potential gradient between subsidiary cells and guard cells forcing water movement out of guard cells. As guard cells lose turgidity stomatal pores close and when the guard cells regain turgidity pores re-open. In eucalypts, guard cell walls contain locally thickened areas on the ventral side. When turgor pressure increases in a guard cell thinner elastic areas of the guard cell on the dorsal side distend, whilst the more rigid inelastic areas bend and open the stomatal pore (Kozlowski, 1972). McDowell *et al.* (2008) state that isohydric plants reduce crown-level stomatal conductance (G_s) as soil water potential decreases and ambient conditions dry out and hence maintain fairly constant leaf water potentials (Ψ_l).

Hydraulic failure may occur within soils and is analogous to xylem cavitation. Hydraulic conductance in soils is a function of soil texture, soil water content, hydraulic conductivity and water table depth. A greater tension is required to pull water through finely textured soils due to the smaller pore size and therefore finely textured soils have a lower conductance than sandy soils when water is abundant (McDowell *et al.*, 2008). In the South African forestry landscape, finely textured soils predominate along the interior of the eastern seaboard in areas such as the Kwa-Zulu Natal Midlands and S.E. Mpumalanga, whilst more sandy coarser textured examples are located along the Zululand coastal plain. Conversely, finely textured soils retain hydraulic conductance for longer at more negative water potentials than coarse textured soils, as the lower conductance of fine textured soils results in slower water loss to transpiration and drainage. Hence, we expect greater hydraulic failure in coarsely textured soils during drought (Sperry *et al.*, 1998).

The depth to a water table is of critical importance as it influences plant hydraulics by limiting plant water uptake during periods of drought (Dawson, 1996; Franks *et al.* 2007). As a means of overcoming a coarse textured soil or deep water table, trees enable soil-to-root conductance by increasing the density of fine roots, enhancing fine root hydraulic conductance and rooting depth (McDowell *et al.,* 2008). Sperry *et al*. (1998) suggest that the ability of a tree to avoid hydraulic failure can be conceptualised using models such as the soil-plant-atmosphere continuum (Figure 2.2).The relationship between leaf water potential (Ψ_l) and evapotranspiration (E) can be modelled on the hydraulic characteristics of soil, xylem tissue, root distribution and root-shoot allocation.

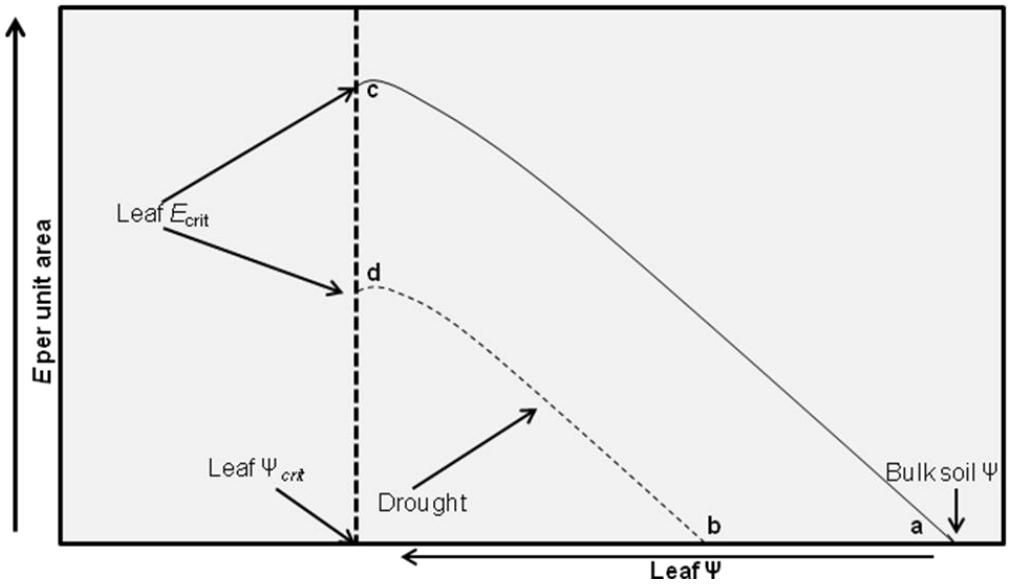

Figure 2.2: Transpiration per leaf unit area as a function of leaf water potential (ΨI) with abundant soil moisture (solid line) vs reduced soil moisture (dashed line) (McDowell et al. 2008)

When E = zero, leaf water potential (Ψ_l) is balanced with bulk soil water potential (Figure 2.2, a). As E increases, Ψ_l decreases (Figure 2.2, solid line a - c) with a drop in water potential becoming greater as drying of the rhizosphere and onset of cavitation reduces leaf specific hydraulic conductance (K_1). If E exceeds evaporation critical rate (E_{crit}), and leaf water potential (Ψ_l) exceeds hydraulic and symplastic limits (Ψ_{crit}), hydraulic failure will occur (Figure 2.2, c). As drought decreases soil water potential in the rooting zone hydraulic failure will start to occur at lower values of E (Figure 2.2 - compare dashed drought trajectory b - d with solid line a - c, abundant water). Drying of the rhizosphere increases the probability of hydraulic failure (Ψ_{crit}) as roots are more vulnerable than stems. A stem can reach greater negative water potentials (-MPa) due to their long hydraulic pathways, but trees that have reached their maximum height are also vulnerable to complete hydraulic failure (McDowell *et al.*, 2002; Sperry *et al*. 2002). Hydraulic failure during drought is projected by plotting the decline in evaporation critical rate (E_{crit}) as a function of soil water potential (Ψ_s) (Figure 2.3). The extraction limit is reached when soil water potential approaches Ψ_{crit} and E_{crit} is zero ($E_{crit} = 0$) and no further soil moisture can be extracted (McDowell *et al.,* 2008).

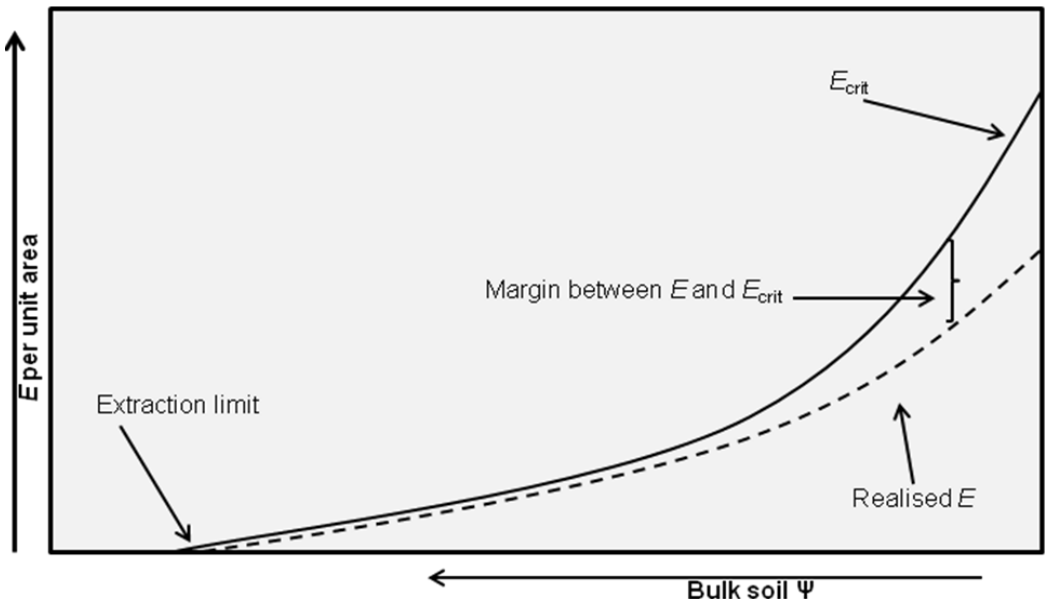

Figure 2.3: Transpiration per leaf unit area as a function of soil water potential (Ψs). Solid line represents transpiration limits beyond which hydraulic failure occurs. Dashed line represents realised transpiration. Difference between the lines equates to a hydraulic safety margin (McDowell *et al.,* 2008)

Tree water use must remain within the realised transpiration margin to sustain growth and hydraulic failure will result if the transpiration threshold is exceeded (Figure 2.3). Trees retain E below E_{crit} for long periods (years) by adjusting structural features that enable maximum water uptake relative to demand by the tree crown. This balance is driven by available water supply, water demand, plant metabolism, and fine adjustments are driven

over time in response to climate, plant size (or leaf area index), soil texture, soil depth and stand density (Maherali and DeLucia, 2001; Mc Dowell *et al*., 2002; Sperry *et al*., 2002; Mencuccini, 2003). Over short periods homeostasis is reached by adjusting stomatal conductance (G_s), i.e. stomatal closure (Tyree and Sperry, 1988; Sperry *et al*., 1998). Whilst reduced G_s limits water loss, it does so at the expense of CO_2 diffusion from the atmosphere to the site of carboxylation (fixation of CO_2 with Ribulose biphosphate (RuBP)) and hence photosynthetic sequestration of CO_2 becomes constrained (Cowan and Farquhar, 1977).

Edwards and Dixon (1995) state that plants respond to drought by maintaining a high water potential or tolerate dehydration by surviving at low plant water potential. Plants that rely on a mechanism of dehydration postponement by increased stomatal resistance (isohydric plants), show reduced transpiration rates and maintain relatively high water potentials in response to drought stress. Trees that rely on dehydration tolerance (anisohydric plants) exhibit osmotic adjustment, a mechanism of turgor maintenance that sustains transpiration at low leaf water potentials. Grier *et al.* (1992) add that certain conifer species resist drought better through the evolution of more cavitation-resistant xylem. Ovalle *et al*. (2015) report that under severe drought, tree species with deep-rooting strategies exhibit a rapid decrease in aboveground biomass of up to 43%. This can be attributed to foliar abscission and thicker root development. According to Bloom (1985), this response is consistent with the resource partitioning theory whereby plants increase the ratio between water absorbing and transpiring surfaces in response to water deficit. Shallow rooting species do not significantly alter biomass balance as a function of water availability and hence die quickly. Padilla *et al*. (2015) conclude that deep rooting forest species develop a great volume of thicker roots able to colonize moister soil and that key to their survival is the longer specific root length able to resist water stress. In contrast, Hoffmann and Kummerow (1978) note that shallow rooting species tend to concentrate fine root production to the top 40 cm of soil. This would appear evident in a specific South African *E. grandis* x *E. urophylla* (Figure 2.4) clone that exhibits a similar root concentration in the upper soil horizon for up to 3 years and suffers widespread mortality before full rotation, even when precipitation is non-limiting and similar findings are reported in Brazil by Mello *et al*. (1999). It is hypothesised that mortality within the clone is due to deep-seated cavitation in the xylem network when roots reach a specific root depth; however, no definitive research exists to indicate whether this tree mortality could also have been due to hydraulic failure or carbon starvation.

Figure 2.4: *E. gxu* clone showing classic shallow rooting system at 4 years of age – Kwambonambi South Africa

Ovalle *et al*. (2015) report that where water availability is high, shallow rooted species produce up to up to 4 times more fine roots as compared to roots in large diameter classes. Hernández *et al. (*2009) note that fine roots improve hydraulic conductance and plant productivity under drought conditions. Bengough *et al.* (2011), Padilla *et al.* (2015), Jin *et al.* (2015) all report that soil dryness strongly affects the capacity of fine roots to elongate due to the low soil matric potential. Ovalle *et al*. (2015), reporting on recent studies, show major differences in the size and structure of xylem networks, resulting in differing capacities to resist embolism and cavitation. Drought resistant species show the highest and least variable xylem water potential (Ψ_w) during summer drought and highlights the difference in water acquisition strategies of tree species with deep and shallow-rooting determining their capacity to survive severe summer drought (Figure 2.4).

Figure 2.5: A and B - *E. gxu* clone showing classic shallow rooting system at 2 years of age – Kwambonambi South Africa. C – Pockets of identical *E. gxu* clone dying in patches at 4 years. D – Staining of cambial tissue of dying trees

Deep-rooted species show better drought performance; independent of watering treatments, but water stressed environments do promote greater root growth of deep-rooted species. Ovalle *et al*. (2015) state that shallow-rooted species prioritise root biomass allocation to thin roots whilst deep-rooted species prioritise root biomass to thick roots (Figure 2.5B); however, both types are able to increase thin root dry mass under greater water availability. In a drought response trial, *Thuja occidentalis* L. (-2.0 MPa predawn water potential) exhibited significantly lower water potential integrals (WPI) than well-watered controls (Edwards and Dixon, 1995). The effect of severe drought on mean transpiration rates of non-conditioned trees and mildly conditioned trees were not significantly different. However, non-conditioned and mildly conditioned trees displayed significant increases in transpiration rates ($p = 0.0001$) in response to severe drought, as compared to moderately conditioned trees, and repeated conditioning to moderate drought (i.e., Ψ_{pd} = -1.4 MPa) resulted in increased tolerance to drought, with moderately conditioned trees retaining high relative water contents (RWC) (McDowell *et al*., 2008). Commercial reforestation must clearly focus on planting deep-rooted species (provided that no new legislation should

disallow this) on stressed, marginal sites, especially where water availability in the first two years of growth may be constrained.

2.6. SILVICULTURE AND ITS IMPACT ON SUSTAINABILITY

The production of high quality planting stock, application of minimum tillage cultivation, planting density, weed control, pest management and fertilisation are all practices that can improve soil water management and drought tolerance. Prior to canopy closure, trees are more responsive to silviculture practices such as cultivation, weed control and fertiliser, whilst soil erosion tends to be higher. After canopy closure, intraspecific competition for resources becomes stronger and in eucalypts, the age at peak LAI coincides with the highest rate of biomass production and evapotranspiration (Ryan *et al.,* 1997; Gonçalves *et al*., 2013). Du Toit *et al*. (2010), in an analysis of the effects, interactions and response mechanisms of intensive silviculture, showed that interventions were additive when implemented simultaneously, emphasizing the need to optimise each practice in the value chain to maximize productivity.

Du Toit (2003) notes that site management during the inter-rotational period (harvesting, slash management and other silvicultural operations) can have a major impact on the productivity and long-term sustainability of short rotation timber plantations, whilst Rolando *et al*. (2002) report the primary aim of sustainable plantation management to be the preservation of site productivity. Managing plantation residues is an integral part of any site preparation and remains highly contentious. Numerous authors, including Little *et al.* (1996) state that the additional costs of establishment in plantation residues, as well as the elevated fire hazards, exacerbate this conundrum. Rolando *et al*. (2002), reporting on results of a residue management trial in Zululand, showed that burning had no negative effect on tree growth. Long-term effects of burning on site productivity have not been fully explained within South African forestry context and hence the lack of significant differences among tree growth rates on sites where residues have been retained or burnt does little to support the argument to halt residue burning. However, it is accepted that the soil erosion risk increases on burnt sites and any soil loss must negatively affect long-term productivity (Little *et al.,* 1996). Rolando *et al.* (2002) concluded that the lack of treatment responses in Zululand indicate that soil physical and nutrient conditions are not limiting and the key resource driving productivity in Zululand, and most forestry areas in South Africa, is water availability.

It is possible to ameliorate factors that limit growth through soil cultivation, residue management, fertiliser applications, weed control, coppice management, thinning and pruning. Nambiar (1998) concludes that the long-term effects of site preparation, including residue management and soil cultivation, on site quality are not fully comprehended, whilst Madeira *et al*. (1989) added that varying methods of residue management and soil tillage might improve growth, although this is site specific. South African research trials generally report no improvement in tree growth under intensive residue management and soil tillage indicating good establishment success is more likely driven by plant quality, planting practices and prevailing climatic conditions. Survival and yield show no significant response to residue management (Rolando *et al.*, 2002). Rolando and Little (2005), Thomas (2009) report that plant mortality is associated with transplant quality, heat, water stress, pests, diseases, and harvest residue management. Rolando and Little (2008) conclude that even where eucalypts are planted on highly productive sites, post establishment mortality can still exceed 10%, resulting in sub-optimal stocking levels and pulpwood yield losses. Reducing the risk of plant mortality associated with unfavourable conditions immediately after establishment is most definitely a management focus to increase the economic viability of plantation forestry, but it is plausible that the financial costs and subsequent benefits of management interventions will have to differ in accordance with species, site and timing of planting.

Few trials have been established in South Africa to assess long term site productivity, especially using tree growth as an index for site productivity (Rolando *et al.* (2002); Titshall *et al*.; 2013). Reporting on a residue management trial in Zululand, South Africa, characterised by low clay content and organic carbon levels, Rolando *et al.* (2002) determined no significant residue management - pitting technique interactions for tree height and diameter at breast height (Dbh) at 14 months. Although differences for treatments were not statistically significant, basal area and volume per hectare were highest in treatments where plantation residues were not burned. Soils typically high in clay content and organic carbon tend to show greater resilience as opposed to coastal sands derived from aeolian deposition, characterised by low clay and organic carbon contents. Hence, recognising the importance of site-specific residue and soil tillage methods cannot be over-emphasized.

2.7. SITE SPECIES MATCHING AND REDUCING SITE STRESS

According to Theron (2000), Herbert (2000), species choice is a key criterion influencing the success of a forestry operation (Figure 2.6). Key factors include proposed timber

market, silvicultural regimes and local environmental conditions, with the most important site criteria, mean annual precipitation (MAP), mean annual temperature (MAT), occurrence of frost and effective soil depth. Disregarding species tolerance seriously affects growth performance and increases susceptibility to biotic and abiotic stressors. Mean annual temperature (MAT) is the most important climatic selection criteria with each species showing an optimum physiological range for fast and continuous growth, as well as resistance to frost, snow damage and disease tolerance. Mean annual precipitation (MAP) herein defines the expected amount of precipitation and monthly distribution, with summer rainfall areas characterized by a marked summer peak in precipitation and relatively dry winters of below 30 mm rainfall per month (Herbert, 2000).

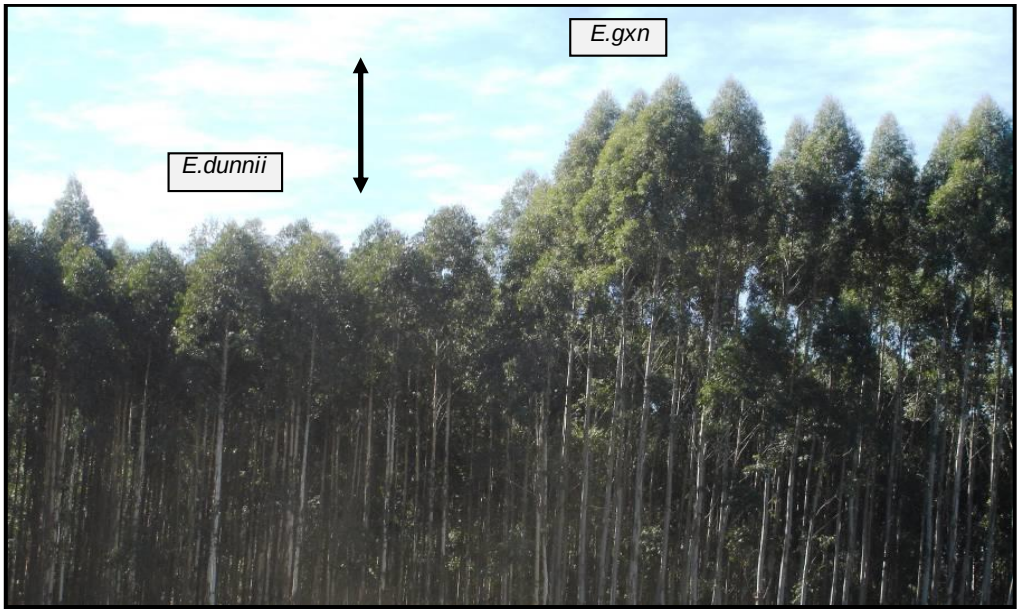

Figure 2.6: Eucalypt species comparison trial at 9 years. Matching correct species to site results in significant volume gains

Important edaphic factors include effective rooting depth (ERD), texture, structure, drainage, fertility and lithology. The ERD of soils, or the depth to a horizon severely limiting effective root growth, include stone-lines, excessive soil firmness due to structure and poorly drained or waterlogged horizons. Soils as the foundation of root physiological activities, including nutrient and water uptake, and respiration, are strongly influenced by texture and structure. Texture class is especially critical in the calculation of plant available water (PAW) of the differing soil forms and families (Herbert, 2000).

Site factors, MAT, MAP and ERD cannot be considered in isolation when evaluating a site (Table 2.1). For example, where soil depth is limited, this can be offset by planting in areas where MAP is higher than the minimum threshold for the species. Similarly, MAP thresholds may be relaxed, if the site is positioned in a water accumulating position in the landscape

(lower slope) where soils are deep and underlain by a well-drained, and friable substratum (Herbert, 2000).

Table 2.1: Summary of preferred temeperate species grown in South Africa

Species	Optimum MAT range (°C)	Min. MAP range (mm)	Alt. range (m)	Min. soil depth** (cm)	Cold tolerance 1-v. high 4-fair	Frost tolerance 1-v. high 4-fair	Snow tolerance 1-v. high 4-fair	Drought tolerance 1-v. high 4-fair
E. dunnii	15.0-19.0	800-950	900 - 1500	35	4	4	4	1
E. nitens	14.0-16.0	825-950	> 1400	45	1	2	1	3
E. grandis	16.5-21.5	900-950	<1150	60	4	4	4	3
E. gra x E. nit	14.0-19.0	850-950	>1200	40	2	2	2	2

(ICFR, 2003 – modified) ** assuming a clay loam texture

2.8. THE ROLE OF NURSERY PLANT QUALITY

Binotto *et al.* (2010) note that a stand of high yielding trees is very dependent on the quality of initial plant stock able to withstand adverse field conditions and grow to economically viable trees. One of the greatest challenges is to identify those characteristics that link nursery stock size to its performance as a planted crop. Reis *et al.* (2008) report that understanding correlations between morphological parameters is key to identifying the best plant stock quality.

Binotto *et al*. (2010) report that seedling production is one of the most important stages in re-establishment of forest stands as it affect final yield, whilst Gomes *et al.* (2002) note that a well-stocked high yielding stand is very dependent on plant quality and must be able to resist adverse field conditions and grow to trees of economically viable volume. Identifying the characteristics that anticipate plant stock size and field performance are challenging and Reis *et al.* (2008) affirm that this is often a subjective process lacking clear definitions to explain plant survival and growth. Morphological variables to determine nursery plant quality include shoot height, root biomass, root collar diameter (RCD), shoot: root ratio, RCD: shoot height (sturdiness ratio), shoot and root, fresh and dry matter mass, and nutritional analysis (Pavia and Gomes, 1993; Gomes *et al.,* 2002). Gomes *et al.* (2002) report that the lower the sturdiness ratio, the more lignified the seedling and greater the general field survival. Wendling *et al.* (2005) show that rating seedlings according to height class can optimise the fertigation of nursery stock, specifically smaller plants; however, Fonseca *et al*. (2002) warn against the separate use of seedling variables, such as height,

to avoid the risk of selecting taller but weaker seedlings whilst discarding shorter studier stock (Figure 2.7).

Figure 2.7: Planting stock optimal for re-establishment. *E. grandis x E. nitens* hybrid clone (left) and *E. dunnii* seedling (right). The clonal genotype requires additional (± 10 cm) height growth to colonise same plug volume

Understanding morphological responses as functions of physiological dynamics is imperative if we are to optimize silviculture processes to exploit favourable planting seasons. Thomas (2009) suggests that a method of drought hardening seedlings is to reduce irrigation, or induce a partial drought stress programme to pre-condition seedlings to the prevailing dry conditions they may experience shortly after planting. Rolando and Little (2005) state that a number of factors can be utilised to monitor water stress, including fluctuations in photosynthetic rate, shoot water potential, transpiration rate, stomatal conductance, chlorophyll conductance, and leaf and stem temperature.

The quality of nursery stock is negated if the saturated hydraulic conductivity (K) that measures the speed with which water travels downwards through soil under gravitational force and influences the time residence of soil water is not optimal. The higher the K value, the greater the flow rate (Papadopol, 2005). Dorsey *et al.* (1990) note several empirical methods to measure hydraulic conductivity but all based on the observation that a sphere of wetting develops around a nucleus in soil. Initially, absorption of water is rapid, speedily

filling empty pores. After the sphere has developed, absorption stabilizes to a constant rate and soil is at its maximum water holding capacity in this sphere. The standard conditions for K measurement begin once this constant rate of absorption has stabilized and sphere formation influence depends critically on texture class. In sands, the sphere is small and forms quickly whilst in clays it is greater and may take more than a day to form. The K-value is a measure of conductivity when soil is moisture saturated and Fotelli *et al*. (2000) describes soil water content (SWC) as a suitably effective drought intensity index.

Although the management of harvest residue plays an indeterminate role in the survival of new plantings, factors such as nursery stock quality and plant size are critically important. A comparative study by South *et al*. (2004), using three container types and a bare-root seedling treatment of *Pinus palustris* seedlings in Louisiana, were out-planted and significant site by treatment interactions recorded. Root-collar diameter (RCD) of container-grown stock positively correlated to root growth potential (RGP) and height after two growing seasons. Container grown stock with the lowest RGP exhibited the lowest overall seedling survival, supporting work by Thomas (2009) who also reported RCD as a useful predictor of field survival. Conversely, Morris (1993) found that survival did not correlate with the RCD of *P. patula* seedlings; however, this was compounded by disparities in seedling age, nursery practice and seedling grading. Guarnaschelli *et al*. (2003) also showed that drought hardened seedlings with a smaller stem diameter survived better infield, whilst Thomas (2009) observed that an increased root: shoot ratio and decreased leaf area, induced through drought hardening, were associated with improved transplant survival in *Eucalyptus pilularis* planted in NSW, Australia.

Kiiskila (1999) reports that under favourable conditions large conifer seedlings, regardless of dimensions, grew better than smaller stock; however, in certain situations larger stock did not always survive as well as smaller stock. Kiiskila (1999) also indicates some contradiction in trials relating seedling size to field performance. Some inconsistencies between various morphological studies could be due to varying growth limiting factors unique to planted sites. On dry sites where weed competition is not excessive but desiccating winds prevalent, smaller seedlings are preferable, as their smaller foliar surface area place less transpiration demands on the root system. Zwolinski and Bayley (2001) state that for a particular container size, survival and growth is poorer in larger, root bound seedlings, than smaller, optimum sized plants. In an *E. grandis* seedling trial by McCubbin and Smith (1991), four nursery container sizes; namely Sappi (49 cavity) white plastic tray, Unigro® (128 cavity) black plastic tray, Speedling® 98 (polystyrene) and Speedling® 128 (polystyrene) showed leaf surface area and mass were significantly greater in seedlings

produced in the Sappi 49 cavity and Speedling® 98 trays. The Speedling® 128 seedlings had a significantly lower root mass at 18 weeks. After transplanting, the Speedling® 128 treatment yielded lower mass increment than seedlings produced in other three container types. Generally, the large container seedlings had higher growth rates than smaller containers.

The effectiveness of drought hardening maybe related to changes associated with limiting water loss or with enhanced water uptake. Drought affected plants tend to limit water loss in several ways, including reduced transpiration (Searson *et al*., 2004; Villa-Salvador *et al*., 2004). Leaf thickness may increase, providing increased leaf volume for carbon assimilation and production of carbohydrates essential for root growth, and less surface area for water loss. Root production following planting may benefit through a prior drought hardening procedure (Thomas, 2009).

2.9. WATER STRESS AS A LIMITING FACTOR

High productivity plantations account for one third of global non-fuelwood supply and the importance of plantations will increase as global wood demands to 9000 million m^3 an^{-1} by 2050 (INDUFOR, 2012). Drought events have become more frequent worldwide and even countries such as Brazil have noted increases in the dry season in scattered regions (Booth, 2013). The effects of water stress are more common in subtropical areas with dry winters and hot summers due to rainfall being unevenly distributed amongst the seasons, with water stress from medium to high (Gonçalves *et al.,* 2017) and a high actual evapotranspiration (AET). Climate change continues to induce stress on many eucalypt plantations due to higher mean annual temperatures, more intense rain events, followed by period of severe water stress (Gonçalves *et al.,* 2013; Gonçalves *et al.,* 2017). Topography and soil characteristics also influence water flow with soil clay content correlating strongly with infiltration rate and water retention capacity, and hence residence time of soil water (Gonçalves 2002). An understanding of the key processes controlling tree growth and water uptake are critical to improve productivity gains without increasing water use. Wood production and evapotranspiration demands depend on the interaction between genetic material, climate, stand age, inherent soil fertility and silviculture input. These factors determine the resource acquisition by leaves and roots, conversion to carbohydrates and allocation to the different tree components (Nouvellon *et al*., 2011) with consensus that timber plantations are predominantly limited by water availability as nutrient deficiencies can be mitigated through fertilisation (Stape *et al*., 2004).

Where water deficits are greater than 400 mm and the dry season extends up to 6 months, timber production is generally economically unviable (Gonçalves *et al.,* 2017). Eucalypts demonstrate a high temporal variation in evapotranspiration rates during a rotation. Soil moisture, leaf area index (LAI), root and water table depth in *E. urophylla x E. grandis* (measured at 52 months in Brazil) showed AET = 1290 mm yr^{-1}, almost equalling the MAP of 1360 mm yr^{-1} (Nouvellon *et a*l., 2011). Soil below 6 m was almost depleted of water and percolation of recently infiltrated rainwater could not penetrate to such depths due to a high AET. By end of rotation, wood growth was entirely limited for prolonged periods of the year. After clearfelling, AET decreased sharply, allowing water to infiltrate to depths below 10 m, approximately 3 months after planting, resulting in a 3 m rise in the water table (Gonçalves *et al.,* 2017). After planting, AET increased rapidly with greater LAI and attained pre-clearfell levels within 16 months. Nouvellon et *al.* (2011) report that deep infiltration of water only occurred 12 – 18 months after planting and for the rest of the rotation, rainfall was recycled to the atmosphere, except when exceptionally heavy rains were recorded.

Leaf traits are closely related to drought tolerance with the number of leaves per unit area, their temporal variation, leaf anatomy and canopy architecture amongst the most important (Whitehead and Beadle, 2004). A high leaf area is generally associated with greater assimilation of carbon (Gonçalves *et al.,* 2017). Tenhunen *et al.* (1987) report that structural and physiological adaptations to drought determine the growth and survival of forest trees in dry climates, whilst Fotelli *et al*. (2000) indicate that water deficits have both long and short-term effects on plants. The opening and closing of stomata occur within minutes (short term) of stress conditions, whereas leaf expansion remains affected over months (long term) and seedlings are definitely more susceptible to drought than saplings or mature trees (Margolis and Brand, 1990; Myers, 1988). A number of factors pertain to the failure of tree plantations, including nursery plant quality, heat and water stress, pests and diseases, and the failure to properly manage harvest residues (Royo *et al*., 2003; Rolando and Little, 2005). Burdett (1990) reports that one of the most important reasons for crop failure is a water deficit, whilst Sands (1984) concludes that following planting, a transplant must establish a root-to-soil interface and commence water and nutrient uptake immediately to survive. According to Grossnickle (2005), mortality following planting will be reduced where transplants are well watered, evaporative loss from leaves is reduced, or root exploration of the bulk soil is stimulated.

Disturbance at the soil-root interface and mechanical damage caused by planting of transplants is accompanied by transplant stress, which will lead to plant mortality or reduced growth. Transplant stress involves a series of physiological and metabolic disorders that

undermine the tree's ability to regenerate and elongate new roots, and a deficiency in plant water status, or any adverse change to water relations will negatively affect survival (Guehl *et al.,* 1993). In a trial at Kruisfontein Estate, Southern Cape, Zwolinski *et al*. (1994), showed that post-plant mortality could be predicted using seedling height, soil concentrations of calcium and magnesium, soil bulk density and penetration resistance. Prolonged water stress and seedling mortality is strongly governed by short-term physiological drivers, followed by long-term morphological, and phenological (plant life cycle events influenced by seasonal variation in climate) responses (Fotelli *et al*., 2000). Grossnickle (2005) reports that soil moisture is the single most important factor contributing to reduced plant mortality of newly established plant stock, even though the role of other physical and cultural factors cannot be dismissed. In the short-term, moisture availability comprises that present in the root plug, whilst in the longer term a tree must absorb moisture from the surrounding soil held under matric pressure. The ability to exploit this moisture is dependent on the ability of roots to grow into soil and the soil-water content. A summation of the above authors indicates that planting under harsh conditions, rapidly induces stomatal stress via transpiration losses within a very short period, a few hours, with long-term effects of such stress permanent.

Rolando and Little (2004) record that biomass allocation, plant moisture content, photosynthetic rate, xylem pressure potential, transpiration rate, stomatal conductance, hydraulic conductance, osmotic potential, chlorophyll fluorescence and leaf and stem temperature can be used as indicators to assess changes in transplant physiology in response to environmental stress. Forrester *et al.* (2010) report no relationship between average daily transpiration of trees and soil moisture measured in the immediate vicinity, and no relationship between sap velocity and average monthly soil moisture at any soil depth for periods of two months or less. Although we accept moisture deficits and heat stress as the primary physical factors causing mortality of eucalypts, including *E. dunnii* and *E. gxn*, it is not always possible to quantify this stress. Figure 2.8 describes the evolution of productivity expressed as mean annual increment (MAI) comparing Brazilian and South African yields (São Paulo University, 2011, modified). Plantation forestry yields are generally limited by water deficit, which in turn, drives a reduction in nutrient uptake in the form of solute. Trees growing under water stress are vulnerable to biotic and abiotic stress and site productivity as a function of effective soil depth; soil fertility and rainfall are the primary drivers of sustainable tree plantations.

The productivity of *Eucalyptus* plantations in Brazil have increased 4 fold in the past 50 years (Binkley *et al*., 2017) with a current average MAI of 41 m^3 ha^{-1} yr^{-1} (ABRAF, 2013).

As productivity increases there is a growing need to understand how gains in wood production influence the utilisation of resources, specifically soil water (Hakamada *et al*., 2020). Studies at São Paulo State University, Brazil, indicate that where soils are deep, mean annual precipitation high, pest and diseases (reducing factors) absent, and silviculture practices optimised, an average MAI of 38 m^3 ha^{-1} yr^{-1} can be realised, with minimal application of highly advanced breeding programmes. Actual MAI (Figure 2.8) can be achieved through optimisation of soil nutrition, especially under increasing soil moisture conditions. To achieve the 'attainable' productivity level (Figure 2.8) of 48 m^3 ha^{-1} yr^{-1} requires an even higher MAP, combined with an optimised nutrition programme (limiting factor) to exploit the benefits of higher soil water. Gonçalves *et al.* (2004) state that optimising eucalypt silviculture targets higher growth rates and short rotations, and eucalypts with their low-nutrient use efficiencies deplete nutrients from a site if nutrient conservation is not a sustainable management practice. The 'potential' productivity of a site is only attainable where defining factors such as advanced tree breeding are incorporated.

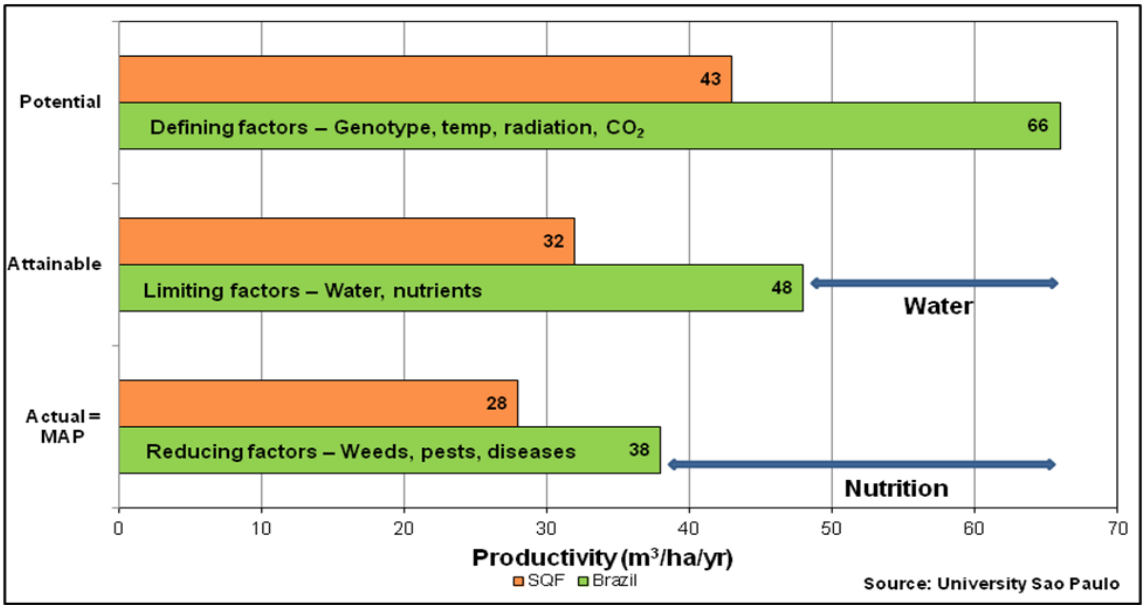

Figure 2.8: Understanding plantation productivity: Water stress as the most limiting factor in plantations linked to nutrient deficiencies and biotic stress. (SQF - A community owned forestry company in Zululand, South Africa) (Modified, Gonçalves *et al.* (2004)

Planting with water or a hydrogel mix, as a buffer to post planting stress has been well-researched (Morris, 1994; Allan *et al*., 2000; Oscroft *et al*., 2000; Rolando and Little, 2004); however, the physiological and morphological benefits of watering are complex with gaps in knowledge for most of the short rotation commercial eucalypts in South Africa. Rolando and Little (2004) state that whilst assessments of mortality may show the response of

planting stock to water stress treatments, they do not improve the understanding that such stress imposes on seedling physiology.

Variations in plant size during early growth stages due to fluctuations in hydration and temperature are well documented. Although variations are small, they may exceed continuous tissue growth through cell division and enlargement. During a growing season, reversible fluctuations in plant tissue mass are accounted for by changing levels in hydration and are much greater than due to diurnal temperature variation (Kozlowski, 1972). Guarnaschelli *et al.* (2006) state that seedlings can be hardened by restricting the volume of water applied for short periods; resulting in a direct impact on water status and gaseous exchange. Lamhamedi *et al*. (2001), Stewart and Lieffers (1993) add that reduced growth and changes in dry mass partitioning, leaf area and root: shoot ratio are the most observed morphological responses to hardening. Nursery stock with a low shoot: root ratio tend to perform better under drought conditions due to a more equable balance between water uptake and moisture loss (Cregg, 1994; Van den Driessche, 1991).

A study of irrigated *Pinus resinosa* seedlings subject to regular irrigation and soil drying treatments revealed that stem diameters of irrigated treatments increased gradually through cambial growth, whereas unirrigated plants contracted cumulatively. Stems of plants in drying soil began to shrink within 5 days of irrigation termination (Binotto *et al*., 2010). Turner and Waggoner (1969) report the development of internal water deficits that induce stem shrinkage lag behind foliar water deficits. Shrinking and swelling of plant tissue reflect a change in energy status of water and impact on cell turgidity whilst turgor dynamics are manipulated by relative rates of absorption, transpiration and internal redistribution of water. During a period of soil drying, cell turgor decreases and plant tissue shrink where atmospheric conditions are conducive to increased levels of transpiration. The rate of net shrinkage during a rainless period is slowed by atmospheric conditions that decrease transpiration, such as cloudy weather. Small amounts of tissue expansion are possible during the night; however, as plants become dehydrated they regain less turgidity at night often resulting in the permanent wilting of foliage (Turner and Waggoner, 1969). The daily contraction and expansion of plant tissue relates to higher transpiration than absorption of water during the day and the reverse at night. During daylight, absorption of water through roots lags behind transpiration due to a resistance to water movement. Any internal water deficit that decreases turgor during the day reduces at night when absorption of water and transpiration are low, but absorption remains the greater force (Kramer, 1969). The above findings corroborated with a study of *Quercus ilex* seedlings where size leaf, leaf number/plant and total leaf area were higher in well-watered treatments compared to

drought-stressed equivalents (Fotelli *et al.* 2000). The behaviour of industrial timber species under conditions of increased competition for resources, climate change and land use change has led to the realisation that the interaction of these factors is not possible without some form of simplification of processes. Complex demands drive the search for fewer candidate traits to explain better the greatest amount of variability (Wilson *et al.,* 1999). It is imperative that these traits are simple to measure; however, expensive equipment that can yield quick accurate results is often difficult to justify financially (Gammon and Surfus, 1999).

Guarnaschelli *et al.* (2006) report that under moist conditions, three provenances of *E. globulus* produced similar total biomass (dry matter), but significant differences were observed amongst water regimes within each provenance *(p* = 0.049). Water stressed sites produced significantly lower RCD, height and leaf area, compared to moist sites; whilst total biomass exhibited a 21% reduction under water stressed treatments. The impact of lower above ground biomass allocation resulted in a 15% decrease in the shoot: root biomass ratio (Guarnaschelli *et al.,* 2006), re-emphasizing that leaf area differences between moist and water stressed treatments were lower in drought tolerant eucalypt species, due to their evolved abilities to allocate lower proportions of biomass above ground, during both wet and dry conditions..

Eucalypt seedlings exposed to water stress preconditioning prior to transplanting experience morphological adjustments whereby biomass, leaf area and shoot total: root biomass ratio, as well as their physiological changes, can be associated with drought hardening (Costa *et al*., 2004; Guarnaschelli *et al*., 2003; Guarnaschelli *et al*., 2006). Importantly, Jacobs *et al.* (2005); Van den Driessche, (1991) report that structural adjustments in leaf area indicate an effective mechanism to reduce moisture loss whilst a greater allocation to roots will definitely improve water uptake, thus allowing a more favourable plant water balance and gaseous exchange capacity under drought conditions. A number of tree root attributes exist that enhance the ability to compete for soil resources scarce in water and nutrients, including the structure of the root system, fine root distribution, seasonality of growth and the physiological ability to take up water and nutrients (Gonçalves *et al.,* 2013).

Eucalypts display dimorphic responses with widely spreading lateral roots just below the soil surface and a deep taproot system in young trees that develops deep sinker roots as trees mature (Knight, 1999). Such roots are opportunistic and grow along gradients of increasing water availability. Although the numbers of fine roots decrease with depth, they are an important survival mechanism absorbing water during seasonal drought. Recent

studies show that fine roots of plantation eucalypts grow close to the water table, up to depths that equate to 85% of average tree height for trees up to 20 m tall (Gonçalves *et al.,* 2017; Christina *et al*., 2011). Mechanisms that enable a eucalypt to cope with periodic and severe water deficits result in reduced growth potential and a root:shoot ratio ranging from 0.8 – 0.12. Soil water content show clones in Brazil able to draw water down to 10 m for the first two years after planting and genotypes with conservative water use mechanisms invest more growth in fine root area relative to leaf area than genotypes adapted to wet regions with a high LAI. (Gonçalves *et al.,* 2017).

Mello *et al*. (1999) report that a stand of 4.5 year old *E. grandis x E. urophylla* clone, showed greater plastic and elastic responses as defined above, to seasonal changes in soil water content than pure *E. grandis* seedlings of the same age. In dry winters, the fine root density (FRD) of the *E. gxu* clone was higher in the upper soil layers (up to 30 cm deep) and during the rainy season, FRD was higher in layers below 30 cm. No significant differences existed between genotypes for cumulative fine root length sampled in winter with approximately 70% of roots found within the upper 30 cm. During summer droughts the cumulative distribution of clonal fine roots were markedly different to those in winter and only 30% of fine roots occurred within the upper 30 cm boundary. During summer, roots were distributed more evenly throughout the soil profile.

Plants can be divided into three distinct hydraulic regulation groups, isohydric, anisohydric and isohydrodynamic. Plants with isohydric characteristics avoid drought induced hydraulic failure by closing stomata (Battie-Laclau *et al*., 2014). When subject to drought, plants will die back through carbohydrate starvation and the inability for gaseous exchange during photosynthesis, leading to reduced resistance to biotic attack. Anisohydric plants are relatively drought tolerant but are susceptible to hydraulic failure as they grow within narrower hydraulic safety margins during a drought event. High temperatures exacerbate carbon starvation and hydraulic failure and biotic attacks increased by drought induced plant stress. Anisohydric types retain xylem flow even when soil moisture is low and will suffer embolisms, or the intake of air into vessel tissue, causing a break in the soil-plant-atmosphere continuum (Battie-Laclau *et al*., 2014). Studies indicate that eucalypts are more isohydrodynamic, an intermediate, whereby the leaf water potential does not remain constant (isohydric behaviour) but does not vary erratically as in anisohydric behaviour. Stomatal openings are partially regulated to allow for high growth rates even when in areas of high water stress. However, when eucalypts are subjected to prolonged water deficit they display the two main drought responses, especially hydraulic malfunctions (Battie-Laclau *et al*., 2014).

Under severe drought, tree species with deep-rooting strategies exhibit up to a 43% decrease in aboveground biomass, attributed to foliar abscission and thicker root development (Ovalle *et al*., 2015). Governed by species evolution, shallow rooting species do not significantly alter the balance of biomass as a function of water availability and die quickly (Bloom, 1985), whilst deep rooting forest species (including *E.dunnii*) develop a greater volume of thicker roots that colonize moist soil. The key to survival is a longer specific root length able to resist water stress (Padilla *et al*., 2015).

2.10. STOMATAL CONDUCTANCE AND DROUGHT EFFECT

Water deficits have short and long-term effects on eucalypts with stomatal opening and closure affected within hours of heat stress, whilst leaf expansion can take months (Myers, 1988). Passioura (1986) reports that water stress research has focused on short term physiological responses that may be of lesser importance over the life of a plant. Incipient wilting, temporary or permanent, is characterised by a slight decrease in turgor pressure and no visual signs of drooping of leaves, and occurs whenever conditions favour high transpiration. Temporary wilting is characterised by leaf droop during the day followed by rehydration and recovery at night. During periods of sustained drying of soil, temporary wilting will regress to permanent with plants not recovering turgidity at night and recovery only possible through direct watering (Kozlowski, 1972). Kramer (1969) emphasises that prolonged permanent wilting will result in tree mortality; with precipitation of no benefit once this threshold is passed. Kozlowski (1972) states that leaf dehydration results in turgor decrease which eventually causes plant wilt, whilst Gardner (1965) reports that visible wilting is driven by specific leaf water potential, governed by species, age and cellular solute content. Cătský (1965) notes that the relative water content (RWC) of plant foliage growing in moist soils are similar but as soil dries, RWC decreases more rapidly in older leaves as opposed to young leaves. Within five days after the initiation of wilting, the RWC of young leaves can be at 45%, with that of older leaves at 80%. Kozlowski (1972) reports that in the early morning, the turgor of leaf cells in wet soils is high. Stomata close during the early stages of water stress, long before visible wilting occurs and remain closed during continued drought with a water loss of just 10% of fresh mass sufficient to induce stomatal closure. There is a direct relation between stomatal conductance and transpiration. As transpiration increases, stomatal conductance decreases, i.e., water is lost during transpiration and water deficit at the root surface increase. When soil water potential is in the range of 0 to -0.1 MPa, stomatal conductance is influenced more by the transpiration rate than soil water potential and hence the need to measure stomatal conductance during the early part of the day (Kozlowski, 1972).

Water deficits increase during a soil-drying cycle and diurnal changes in leaf water deficit occur, with deficits lowest at night. As soil dries, leaf turgor declines as the plant water deficit is higher than the deficit in soil moisture. Finally, when turgor pressure drops to a critical level, foliage reach a permanent state of wilting. Slayter (1967) describes this as occurring when the water potentials of foliage, roots and soil around roots are equal and turgor pressure is zero. Gardner and Ehlig (1965) note that when turgor pressure exceeds 2.0 bar (0.2 MPa), leaf thickness is relatively constant; however, below this threshold the elastic modulus decreases rapidly allowing leaves to wilt.

Kolb and Robberecht (1996), in a study of the impacts of high temperature and drought on the survival, growth and water relations of *Pinus ponderosa* (Dougl.) Lawson seedlings, record that the soil surface and adjacent 5 mm of air reached temperature of 75°C whilst those 50 mm above the soil did not exceed 45°C. These recordings are well in excess of the lethal temperature that physiological mechanisms in a plant can withstand. No correlation between seedling mortality and needle temperature exist but seedlings that survive after exposure to such high heat reveal higher stomatal conductance levels than those that did not survive until autumn. Relative humidity is extremely sensitive to temperature fluctuations. A lowering of ambient temperature causes an attendant rise in RH as the capacity of air to hold moisture water vapour lowers with cooling. After cooling, the existing amount of vapour represents a higher percentage of the total moisture holding capacity of the volume of air (Strahler and Strahler, 1987). Providing tree seedlings with sufficient access to soil moisture, allows for a greater tolerance to moderately high ambient temperatures. High stomatal conductance and transpiration rates are the most effective mechanisms to avoid heat damage and water transport mechanisms act to cool the stem to below lethal temperatures (Little and Rolando, 2004; Kolb and Robberecht, 1996). Heat exchange calculations show that rapid water flow through the stem can reduce bole temperature by 30°C during periods of maximum sunlight; however, under drought stress, plants have to either transpire to stay cool, until a water deficit kills it, or close stomata and risk tissue damage (Beadle and White, 1968). This response is controlled by the level of drought conditioning the seedling has undergone, but can never exceed the genetic threshold of the species.

Bartlett et *al*. (2012) report that drought is one of the greatest challenges facing species worldwide and greater quantification of tolerances are needed, whilst Guarnaschelli *et al.* (2006) emphasize that establishment is one of the most critical phases during a tree crop rotation due to the range of stressful conditions that may compromise later performance. Water stress is induced by limited contact between roots and soil (air pockets), poor

hydraulic conductance of suberized roots or root confinement (shallow effective rooting depth). Physiological changes to water stress include osmotic adjustment, elastic adjustment and stomatal regulation. Edwards *et al*. (1995); Fan *et al*. (1994); Stewart *et al*. (1993); Zwiazek and Blake (1990) state that osmotic adjustment ensures plants maintain turgor through the net accumulation of solutes and facilitates turgor dependent processes such as stomatal opening and gaseous exchange under drought stressed conditions. Bartlett *et al*. (2012) recognise leaf water potential at turgor loss or wilting (π_{tlp}) as a major physiological determinant of plant water stress. However, the cellular structure of (π_{tlp}) and its importance for predicting ecological drought tolerance are controversial. In a meta-analysis of 317 species from 72 studies, π_{tlp} values strongly correlated with moisture availability within and across biomes, indicating the ability of species to predict or anticipate drought responses. The genus *Eucalyptus* has a number of extremely drought tolerant species with an innate ability to sense declining soil moisture.

Bartlett *et al.* (2012) derived equations expressing wilting (π_{tlp}) and relative water content at turgor loss point (RWC_{tlp}) as functions of osmotic potential at full turgor (π_o) and bulk modulus of elasticity (ε), or the decrease in cell turgor with the loss of water in the leaf. Saito *et al*. (2006) describe ε as the ratio of change in leaf cell turgor (P) relative to the cell volume ($\Delta V/V$) of the leaf [$\varepsilon = \Delta P/(\Delta V/V)$], as derived by the pressure volume (P - V) technique (Scholander *et al.,* 1965). A decrease in turgor results in a decrease in leaf water potential and produces the driving force for reduced water flow in the soil–plant–atmosphere continuum. Analyses indicate that osmotic potential at full turgor (π_o) is the major driver of wilting (π_{tlp}). Conversely, modulus of elasticity (ε) plays no direct role in drought tolerance, but sclerophylly and elastic adjustments act to maintain turgor loss point, thus preventing cell dehydration, and offering some protection against nutrient, mechanical and herbivory stresses, independent of drought tolerance. Tyree *et al*. (1982) add that tissue elasticity allows plants to lose moisture before reaching turgor loss point and this physiological mechanism contributes to better performance after planting. During an imposed 6-day drought period after preconditioning, acclimated *E. globulus* seedlings plants showed higher stomatal conductance, predawn relative water content, water potential and greater survival than non-acclimated plants (Guarnaschelli *et al*., 2003); (Guarnaschelli *et al.,* 2006); (Sasse *et al*., 1996).

Research from SE Brazil on *E. grandis* has shown that increasing LAI through the application of potassium (K) fertiliser can be harmful to plant tolerance during periods of water stress (Battie-Laclau *et al*., 2016). Although K is critical in the regulation of stomata, it may also induce a higher transpiration rate resulting in water stress whilst the application

of nitrogen (N) could increase stress and mortality of plants during dry periods (Stoneman *et al.*, 1996). These outcomes may be governed by genotype x environment interactions.

2.11. THE ROLE OF VAPOUR PRESSURE DEFICIT (VPD)

Air is saturated when it reaches maximum water holding capacity at a given temperature (dew point) and vapour pressure (vpair) a measure of how much water, in gaseous form, is present. When air attains maximum water vapour content, saturation vapour pressure (vp_{sat}) is directly related to temperature. The difference between saturation vapour pressure and actual air vapour pressure ($vp_{sat} – vp_{air}$) equals VPD (Prenger and Ling, 2015). Chaney and Kozlowski (1969) report that foliar shrinkage and expansion relate to environmental conditions affecting stomatal opening. Changes in leaf thickness negatively correlate with VPD. When VPD increases, leaves shrink and as VPD decreases, leaves expand with the chlorenchyma, endodermis and transfusion cell tissues (parenchyma cells and tracheids) driving change. The negative correlation between leaf shrinkage and VPD is pronounced when soil moisture is high as opposed to low. Leaf thickness begins to decrease at sunrise as VPD increases and continues to do so until late afternoon when VPD starts to decrease; however, under drought conditions, the expansion and contraction effect decreases progressively until it becomes negligible. Under severe drought, foliage contracts at sunrise and will continue to do so until near sunset, rather than just before sunset, for those plants not drought stressed.

Drought induces stem shrinkage in both angiosperms and gymnosperms show radial decrease to be most prominent in late summer when soil moisture levels are depleted Kozlowski (1972). Trees can remain in a dehydrated and shrunken condition for more than three months until soil moisture is recharged by rains and not due to an increase in atmospheric moisture. A high VPD indicates air has a greater capacity to hold water, thus stimulating transpiration (water vapour transfer) into the atmosphere under low humidity. A low VPD points to air near saturation that cannot accept moisture from the leaf under high humidity conditions. Hence, VPD expresses vapour flow in the system, in terms of both condensation and transpiration. A higher VPD increases transpiration from leaf surfaces to the atmosphere; in contrast, a low VPD indicates a proximity to dew point, where condensation can develop and canopy temperature is the best indicator of VPD, especially as dew point approaches (Prenger and Ling, 2015). A Brazilian study of eight eucalypt clones under normal and water stressed conditions demonstrated that decreased stomatal conductance with increasing VPD and drought tolerant clones presented lower sensitivity to VPD under stress conditions than drought sensitive clones (Gonçalves *et al.,* 2017).

Clones all increased the number of stomata and reduced leaf thickness after water stress periods. Lower stomatal density protects against water stress conditions as fewer stomata reduce the transpiration area (Hamamishi, 2015; Otto, 2015). Fungal pathogens have shown to better survive at a VPD ≤ 0.43 kPa and are most damaging below 0.20 kPa (Prenger and Ling, 2015).

2.12. IMPACTS OF WATER STRESS

Plant growth is determined by plant water stress and only partially by soil water status. Plant water potential is a measure of water stress and includes soil water deficit, evaporative demand, soil temperature, plant nutrient status, root density, and root distribution. Although these variables fluctuate, plant water potential is an immediate measure of their combined net effect on plant water status (Kramer, 1969; Myers and Landsberg, 1989).

Guarnaschelli *et al*. (2003), in a study of *E. globulus* subsp. *bicostata,* state that the processes involved in drought acclimation have not been fully expounded, nor how physiological and morphological mechanisms interact to bring about moisture stress tolerance in provenances from contrasting sites. Myers (1998), Myers *et al.* (1989), describe the water stress integral, (S_ψ), as a cumulative measure of pre-dawn leaf water potential (ψ_e) over a time period and explains the relationship between water status and tree yield, including long term variability in growth patterns. The water stress integral has shown to correlate with basal area increment and final needle length in *Pinus radiata*. Myers (1998), Myers *et al*. (1989) state that Sψ can be estimated from the formula:

$$S\psi = \sum_{i=0}^{i=t} \psi_{i,i+1} - c)n]$$

Where $\psi_{i,\,i+1}$ = mean of predawn leaf water potential (ψ_e) for any interval i, i + 1, and c the maximum ψ_e measured during the study (indicated as negative MPa). Myers (1988) notes that in calculating Sψ, stress is reflected in ψ_e (leaf water potential) and causes a reduction in growth; i.e. the lower ψ_e, the greater the reduction in growth. Mild water stress is sufficient to have negative effects on canopy size if prolonged and will have a significant effect on annual growth increment. Myers (1988), reporting on *P. radiata*, showed that final needle length and basal area increment were closely correlated (r = 0.90) with tree water stress but poorly correlated with cumulative soil water deficit. This suggests that growth stress reflected in ψ_e and Sψ is not solely driven by soil water deficits with no unique relationship between Sψ and soil water deficit.

In irrigated trees, the relationship between water stress integral (Sψ) and nutrient status is inverse (Myers, 1988; Wang *et al.*, 1988). Where ψ_e is above -0.9 MPa, a strong linear correlation between Sψ and tree nitrogen status (r= 0.81, 0<0.01) exists. Under dry land conditions, Sψ is governed by low ψ_e values during summer drought. When soil water deficits are large, Sψ values increase rapidly, nutrient uptake becomes limited and hence Sψ clearly determined by soil water deficit. However, Hillerdal-Hagstromer *et al*. (1982) in a study of Scots pine (*Pinus sylvestris*) showed that improved stomatal control of water loss to be the greatest cause of higher midday values of water potential in fertilised trees.

Myers and Landsberg (1989) report that water stress causes large differences in growth rates, leading to significant differences in dry matter produced at 6 weeks for *E. maculata* and 10 weeks for *E. brockwayi,* but species differences were greatest at 100 (T_{100}) days and lowest at 40 (T_{40}) days. Reductions in leaf area were ascribed to a reduction in the rate of leaf emergence and average leaf size, with a 20% difference in leaf size between T_{100} and T_{40} *E. maculata* seedlings, with a fivefold difference in average number of leaves per seedling. Reduction in average leaf size of water-stressed seedlings was associated with a reduction in the rate of leaf expansion and an increasing proportion of young expanding leaves. At termination of the experiment, the T_{100} seedlings had a greater proportion of young expanding leaves than water stressed seedlings. Water stress caused a more pronounced reduction in dry matter production in *E. maculata*, a species from a moist biome, than *E. brockwayi,* which grows naturally in an arid environment, and demonstrated that moderate water stress over a long period has a more detrimental effect on growth than a severe stress for a short period. Similarly, transpiration rate of plants were not affected by the intensity of applied water stress, but species and plant size were. *E. brockwayi* showed a higher transpiration rate than *E. maculata*, whilst the net assimilation rate was two to three times greater in the dry-habitat species. The use of the water stress integral (S_ψ) demonstrated a secondary effect of water stress, namely the reduction in growth due to a reduction in leaf area.

2.13. SPECIFIC LEAF AREA (SLA) AND RELATIVE GROWTH RATE (RGR)

Opinion has begun to coalesce around three major axes responsible for variation in plants. The first, the capacity for competitive dominance, is entirely reliant on plant size (Gaudet and Keddy, 1988; Hodgson *et al*. 1999). The second axis is referred as the response to disturbance. Grime *et al*. (1997) state that the third, and most important in single species stands, is resource use or capture axis, and is the trade-off between traits that are advantageous in resource rich environments, including rapid rates of resource acquisition

and loss, high rates of tissue turnover and the conservative strategy prevailing in resource-poor environments.

Costa *et al*. (2004); Guarnaschelli *et al*. (2003); Guarnaschelli *et al*. (2006) confirm that eucalypt (*E. globulus)* seedlings exposed to water stress preconditioning (prior to transplanting) experience morphological adjustments whereby total biomass, leaf area and shoot: root biomass ratio, as well as their physiological changes are associated with drought hardening and similar findings exist for *E. dunnii* and *E. gxn.* Importantly, *Jacobs et al.* (2005); Van den Driessche R, (1991) report that structural adjustments in leaf area indicate an effective mechanism to reduce moisture loss, whilst a greater allocation to roots would almost definitely improve water uptake, thus allowing a more favourable plant water balance and gaseous exchange capacity under drought

Drought preconditioning of seedlings in the nursery reduces leaf area; optimises plant water balance and gaseous exchange capacity. When combined with a good watering at planting, survival is improved. This is in direct contrast to nursery drought preconditioning, followed by extended dry field conditions, with no significant recharge of soil moisture (Costa *et al*., 2004; Guarnaschelli *et al*., 2003; Guarnaschelli *et al*., 2006). Guarnaschelli *et al*. (2006) report that *E. globulus* seedlings well-watered in the nursery, but followed by 40 days of no watering, post-planting, showed lower survival rates (60 - 80%) than transplants subject to drought preconditioning in the nursery (never irrigated to less than 10% field capacity) followed by 40 days of no watering after planting (73 - 86%).

Drought preconditioning in *E globulus* creates several adaptive physiological changes in osmotic adjustment whereby water moves into cells maintaining the pressure potential through active solute accumulation. However, a simultaneous increase in apoplasmic water fraction, causing cell reduction, may also lower the osmotic potential in stressed plants (Correia *et al.,* 1989; Guarnaschelli *et al.;* 2001; Guarnaschelli *et al*., 2003; Pita *et al.,* 2001; Wang *et al.,* 1988). Nielsen *et al.* (1996) indicate that this passive osmotic adjustment reaches a peak during growing periods. Species able to overcome water stress tend towards a low osmotic adjustment and low bulk modulus of elasticity by keeping cell turgidity at low relative water contents (RWC).

2.14. WATER STATUS AND NON-STRUCTURAL CARBOHYDRATES IN FOREST TREES

In a study by Guehl *et al*. (1993), predawn leaf water potential was significantly lower in drought-conditioned seedlings (-0.81 MPa) than well-watered treatments (-0.41 MPa). No white root tips were observed in drought-conditioned seedlings, whereas all seedlings in the well-watered treatment showed active root growth. Fructose and glucose concentrations increased under drought stress in needles and roots, but not significantly so. In roots, the lowest starch concentrations occurred in drought-conditioned seedlings, whilst sucrose did not appear in the needles of either treatment. Guehl *et al.* (1993) report that transplanting did not affect soluble carbohydrate concentrations in needles or roots of pine seedlings. Starch concentrations in roots were highest in watered seedlings and lowest in drought-conditioned seedling. In direct contrast to the findings of Aussenac *et al.* (1988) reporting on *Cedrus atlantica*, Guehl *et al.* (1993) report that drought conditioning decreased needle water potential, bud development index and increased mortality. Drought conditioning did not result in a significant increase in soluble carbohydrate concentration in Corsican pine as noted in other species (Munns and Weier, 1981; Thomas, 1990; Zwiazek and Blake, 1990). Li and Li (2005) have demonstrated changes in non-structural carbohydrate biosynthesis and activities of enzymes in the leaves of apple plant (*Malus domestica* Borkh. cv. "Nagano-Fuji') in response to water stress, specifically enzymes associated with sorbitol, sucrose and starch metabolism. Water stress resulted in the accumulation of photosynthates in the leaves, mainly sorbitol, sucrose, glucose and fructose, whilst there was a reduction in starch concentration. Correlation and path analysis studies revealed water stress affected the partitioning of fixed carbon among terminal products.

Planting may result in a decline in the CO_2 assimilation capacity of seedlings, albeit temporary. An impairment of photosynthesis in planting stock may cause the rate of photo-assimilate utilization to exceed photo-assimilate production, resulting in carbon and energy metabolism becoming dependent on the utilization of non-structural carbohydrate reserves. A depletion of carbohydrate reserves results in a loss of root regenerating ability if the quantity of reserve organic molecules in the roots or other plant compartments is less than required for metabolic processes involved in the formation of new roots (Puttonen, 1986). Depressed photosynthesis at planting, combined with drought stress, will bring about competition for metabolites between the processes of growth and osmotic change. In some species, drought conditioning enhances plant regrowth and root regeneration after the relief of a water shortage and the mechanism underlying this effect involves soluble carbohydrates that accumulate during drought (Guehl *et al*., 1993). A study of

Mediterranean plants showed that to counter environmental limitations, drought tolerant trees develop structural and functional systems to resist water stress and early mortality. Amongst their findings was the ability to assimilate carbon, water use, and resistance to xylem cavitation, maintaining photosynthetic capacity and stomatal closure, all during periods of prolonged drought (Ovalle *et al.,* 2015).

2.15. THE ROLE OF NUTRIENTS IN EUCALYPTS

Despite a long-standing claim that species differ in nutrient demands, studies do not support this statement (Binkley and Giardina, 1998). The understanding that nutrient cycling and nutrient availability is higher under broad-leaved than needle-leaved trees is not supported by experimental evidence. Higher rates of litter decomposition and N mineralization of aspen (*Populus tremuloides* Michx.), relative to conifers, has been reported in some studies, but in others, rates of N mineralization in birch forests has been equal or lower than coniferous forests (Prescott, 2002). Similarly, faster decomposition of broadleaf litter than needle mat is reported for many studies, whereas others report no difference. Long-term incubation of broadleaf and needle litter suggest that the faster decay of broadleaf litter is short-lived. However, the litter of many broadleaf species has a higher base cation concentration and does create forest floors higher in base cations and pH (Brantburg *et al*. 2000). Some of the supposed variability in the effects of species on nutrient availability relate to site factors. Comparing pure stands of four conifer species on four varying sites, Prescott *et al.* (2000c) found that forest floor N mineralization rates are influenced more by site, slope position and ground vegetation than tree species. Fyles and Cote (1994) established that although the litter produced by tree species influences nutrient cycling, it is not the dominant factor.

Grove *et al*. (1996) state that eucalypts have evolved predominantly on the Australian continent where nutrient availability is low and limits tree growth. Survival and growth on such soils depends on mechanisms that enhance nutrient uptake and contribute to efficient use and retention of nutrients within the tree. A mechanism contributing to efficient uptake is the symbiosis between fine roots and ectomycorrhizal fungi occupying different niches in soil-litter layers, and utilize mechanisms to enhance N and P uptake. The uptake of immobile nutrients, such as P, increase through greater exploration of the soil volume by fungal hyphae. Native eucalypt forests possess particularly low levels of P concentrated in above ground components and contain lower levels of N than Northern Hemisphere species. Proportionally, more dry matter and nutrients are contained within the roots of eucalypts growing in low nutrient or dry environments than on moister, higher nutrient sites.

Foliage retains a major proportion of the above ground N and P in young trees whilst stems and branches of older eucalypts contain most of the tree's nutrients and are major sinks for additional nutrients absorbed when reserves in the soil are increased (Grove *et al*., 1996).

Strategies that contribute to efficient use of nutrients by eucalypts and to their ability to survive and grow in low nutrient environments include the genetic regulation of maximum growth rates, the capacity to store and re-use nutrients in excess of current requirements for growth and the strong development of biochemical cycling (Grove *et al*., 1996). Nutrient translocation from senescent leaves and wood, in transition from sapwood to heartwood, are the major components of the biochemical cycling of N, P and other mobile nutrients. Retranslocation of phloem-immobile nutrients such as Calcium is a minor component of nutrient transfer within the tree (Grove *et al.* 1996), whilst Smith and Du Toit (2005) note that the incorporation of harvest residues to be beneficial for the rapid release of nutrients and improved eucalypt growth in warm to hot climes. Brazilian and South African studies note increased ammonification in top soil horizons through incorporation of harvest residue, whilst N and P uptake in 1 - 2 year old eucalypt stands are higher where residues are disturbed or burnt as opposed to *in situ* conservation of residue. Nutrient benefits do not necessarily express in greater volume at final rotation and the initial uptake may be curtailed once the biogeochemical cycle is fully activated after canopy closure (du Toit and Dovey, 2005; du Toit *et al*., 2008).

Nutrient concentration ranges are well reported for eucalypts in South Africa, mostly focused on *E. grandis,* with literature generally more than 20 years old. Defining the nutrient concentrations for both deficiency and toxicity automatically defines the optimum range (Smith and Loneragan, 1997). Knight and Nicholas (1996) note that foliage concentrations of N and P can be insensitive indicators of supply as a deficiency in either can reduce dry matter production without causing a reduction in concentration. Turner and Lambert (1986) report when one nutrient is involved in the metabolism of another nutrient, specific symptoms may not be clearly differentiated, e.g. N and S are biochemically intertwined in plant protein synthesis. In many forest species, available S limits protein formation with symptoms of N and S deficiency similar. According to Gonçalves *et al*. (2004), soon after planting, root systems increase exploration of soil volume and competition for nutrients. However, initial growth is inhibited by physiological constraints to light capture due to drought stress or by turgor relations obstructing root development.

Seedlings allocate a large portion of photosynthates and nutrients to root growth during the first few months after planting to exploit soil water and nutrients. Thereafter, they are

redirected to leaf development once solute supply from root systems is sufficient to meet shoot growth. The balance between root and shoot development fluctuates continually as trees grow and where solute supply is adequate, photosynthetic activity will be maximized and canopy, and root systems will proliferate rapidly (Nambiar *et al.,* 1984; Gonçalves *et al.,* 2000).

Highest rates of N and P uptake by eucalypts occurs during the year prior to peak LAI at canopy closure, with increased rates of nutrient uptake prolonging leaf retention and photosynthetic efficiency (Barros *et al*., 2000; Gonçalves *et al*., 2004; Smethurst *et al.,* 2003). Greater uptake also affects partitioning in eucalypts by increasing the allocation of foliage at the expense of root development. After canopy closure, internal and external nutrient cycles are increasingly important as light and water become limiting (Cromer *et al.,* 1993; Grove *et al*., 1996; Gonçalves *et al.,* 2000). Smethurst *et al.* (2003) note an N deficiency in *E. nitens*, post canopy closure, when LAI was less than 4 m^2 m^{-2}, whilst Gonçalves *et al.* (2004) report a peak LAI of 3 m^2 m^{-2} in the tropics, with nutrient deficiencies likely to occur prior to this. Ingestad (1982), Cromer (1984), Cromer *et al*. (1984) report eucalypt seedlings remain healthy at low concentrations of foliar N, if continuously supplied with N, whilst Negi and Sharma (1996) indicate higher foliar nutrient concentrations on fertile versus infertile sites, with a two-fold increase in N, P, K and Mg. Conversely, in a study of 2-year-old *E. globulus* (Cromer, 1996), mean foliar concentration was significantly lower in fertilised than unfertilized plots, despite fertilised foliar biomass being almost 6 times greater. This was clearly a nutrient dilution effect brought about by faster growth rates.

Under infertile or dry conditions eucalypt leaves become sclerophyllous with Medina (1983) suggesting that sclerophylly may be characterised by low concentrations of N and P, and a high ratio of N:Ca. Eucalypts grown in fertile Indian soils reveal a lower degree of sclerophylly and suggest the evolution of a different strain or 'ideotype' according to soil nutrient status. As sclerophylly decreases, associated decreases occur in leaf longevity, combined with residence time of nutrients in leaves and carbon gain. As sclerophylly increases so does the longevity and residence time of nutrients and increased sclerophylly could be associated with a positive correlation in nutrient use efficiency (Negi and Sharma, 1996). Foliar nutrient concentrations are sensitive to site differences and play an important role in the identification of nutritional deficiencies and imbalances; however, conflicting findings by authors may reflect differences in eucalypt species and their abilities to store foliar N. Whilst much of the development of foliar analysis in agricultural crops has aimed at deriving critical nutrient concentrations, there has been a greater emphasis in identifying nutrient ratios in eucalypts (Cromer *et al*., 1981; Schönau, 1981; Schönau and Herbert,

1983). A number of workers have identified foliar N: P ratios as particularly sensitive to fertilisation for plantation grown eucalypts with Cromer *et al*. (1981) suggesting an optimum N: P ratio = 15 for *E. globulus* and *E. sieberi*, whilst an ideal ratio for *E. grandis* in South Africa = 13 (Schönau and Herbert, 1989).

Foliar samples taken when nutrient concentrations are stable and trees under maximum stress are the most reliable for diagnostic purposes (Will, 1985). Studies of seasonal changes in foliar nutrient concentrations of eucalypts (Table 2.2) identify seasonal fluctuations for all nutrients. Australian data collected over 25 months suggest that foliar concentrations of N, P, Ca, Cu and Mn in *E. saligna* are at a minimum in midsummer (February to March) and this may be the optimal time to sample eucalypts in the Southern Hemisphere. Not all nutrients follow the same pattern, with Mg and K concentrations lowest in spring and midwinter (Knight and Nicholas, 1996). Schönau (1981), reporting on monthly foliar nutrient concentrations for *E. grandis* in South Africa showed greatest differences in summer and lowest in winter. Foliar N, P, S and Cu decreased with age, whilst K, Ca, Mg, Zn and Mn were constant, with only Fe tending to increase. Concentrations of N, Ca, S, Zn and Fe varied with rainfall, whilst P and Cu varied with temperature (Table 2.2).

Table 2.2: Seasonal responses in *Eucalyptus* foliar nutrient concentrations

Nutrient	Summer analysis	Winter analysis	Spring response	Age responsive	Temp responsive	Rainfall responsive
N	AS			S ↓		S
P	AS			S ↓	S	
K	S	A				
S	S			S↓		S
Ca	AS					S
Mg	S		A			
Zn	S					S
Cu	AS			S↓	S	
Mn	AS					
Fe	S			S↑		S

A - Australian reference; S - South African reference; ↓ - Concentration decrease; ↑ - Concentration increase

A single sampling time to analyze nutrient status (Table 2.2) may not be accurate (Bell and Ward, 1984). Schönau (1983) records that optimally sited eucalypts grow virtually all year, with sampling recommended at the height of the growing season (summer) when differences between nutrients are most pronounced. Conversion to dry nutrient mass may be a complementary approach to foliar analysis using regression techniques, whereby canopy foliar nutrient concentrations and ratios are compared alone or in combination with some index of tree growth. In *E. deglupta* Blume, Lamb (1977) could explain 72% of variation in height growth at 15 months, through foliar N and P concentrations. By including K concentrations and ratios of N, P and K, Judd *et al*. (1996) accounted for 74% of variation

in diameter growth for *E. globulus* at two years. Whilst regression techniques may be useful at an early age (up to 2 years), particularly for monitoring responses to fertiliser applied at establishment, their value diminishes thereafter and can lead to errors in final treatment recommendations. As trees mature and nutrient and water use increase, competition limits growth. If one or more resources are scarce, growth vigour will decrease at an early age although Cromer *et al*. (1981) report no relationship between concentrations of foliar nutrients and growth for eucalypts four years after planting.

2.15.1. MACRO NUTRIENT INTERACTIONS IN EUCALYPTS AND THEIR IMPACT

In Brazil and South Africa, N, P and K fertiliser applications of eucalypts are based on the concentration of soil organic matter (O.C.), clay, Bray P and exchangeable K. This extrapolation based on the understanding that O.C. and clay content, besides relating to the availability of N, P and K, affect site productivity through their water availability characteristics (Gonçalves *et al*., 2004).

Olsen and Bell (1990) state that the relationship between growth and nutrient status in eucalypts is complex as they utilize readily available nutrients to support new growth, sometimes leading to a dilution of tissue concentrations. Nutrient concentrations in eucalypt foliage vary seasonally, with leaf ontogeny, leaf age and position in the crown (Lamb, 1976; Bell and Ward, 1984, Leuning *et al*., 1991). In *E. diversicolor,* Grove (1990) reports that twigs to be more effective in diagnosing deficiencies and predicting N, and P requirements, whilst Cromer (1996) notes bark and xylem sap analysis yield better results than leaf tissue in detecting nutrient deficiencies. The three youngest mature leaf blades appear the most sensitive indicators of N in eucalypt seedlings, whereas stems and petioles are better indicators for P (Olsen and Bell, 1990). Dell *et al.* (2001) recommend sampling the first pair of fully expanded leaves on youngest shoots in the late summer growing period.

Using excised tree roots as an indicator for the demand of P, Harrison and Helliwell (1979) showed that a measure of influx of ^{32}P-labelled phosphate solution into roots correlated well with tree growth and inversely with phosphate supply to the tree. Dighton *et al*. (1993), Jones and Dighton (1993) applied a modification of this bioassay technique to determine N, P and K demands for *E. grandis* seedlings that proved more effective than foliar analysis. Herbert (1996) reports that increased nutrient uptake following fertiliser application does not necessarily indicate better growth, nor does a decrease in nutrient concentration result in poorer growth. Optimized growth requires a balance of nutrients with nutrient ratios all approaching their optima. Some ratios are more important and if ratios of N: P, N: S, P: K

and Ca: Mg are close to their optima, it is unlikely that growth rate can be increased through fertilizing.

Nitrogen (N)

N is a constituent of amino acids, proteins, nucleic acids, chlorophyll, co-enzymes, ATP, alkaloids and a structural component of cell walls (Table 2.3) (Dell, 1996). Trees require large concentrations of N as amino acid complexes contain N and the proteins they constitute half the dry weight of the cell (Landis and Van Wordragen, (2006). An early symptom of deficiency is leaf chlorosis due to reduced chlorophyll formation, whilst carbohydrates may accumulate as they are not utilized for protein synthesis. Nitrogen is readily mobile in the phloem and any surplus accumulates in mature, non-senescent leaves (Dell, 1996). Gonçalves *et al*. (2004); McGill and Christie (1983) report that the deficiency of N is closely associated with the exhaustion of mineralisable C. Sheriff and Nambiar (1991) state that the efficient utilisation of N by leaves in accumulating C depends on how N partitions to compounds involved in photosynthesis versus other substances. The efficiency of N utilization in carbon assimilation is greater at higher N concentrations, but can vary amongst species. The efficient use of water by leaves in carbon accumulation is dependent on rates of C assimilation and transpiration. Leaf conductance correlates positively to foliar N concentration, but quantitatively, the relationship varies within species.

Table 2.3: Summary of functions of essential macro elements in higher plants

Element	Physiological process	Constituent of metabolite or cell component
N	Amino acid complex contains N. Proteins constitute ½ the dry weight of a cell	Amino acids, proteins, nucleic acids, nucleotides, chlorophyll
P	Energy storage and transfer, membrane integrity	ATP, nucleotides, nucleic acids, phospholipids
K	Translocation, water relations, energy relations, stomatal opening, regulation of cellular pH, osmo-regulation, cation-anion balance	
S	Protein synthesis and function, energy transfer, structure	Amino acids, co-enzymes, ferredoxins, sulfolipids, proteins
Ca	Membrane maintenance, cell division and elongation, cell wall stabilization, cation-anion balance, osmo-regulation, second messenger in environmental signals	Calcium pectates
Mg	CO_2 assimilation, regulation of cellular pH, cation-anion balance, protein synthesis, carbohydrate partitioning	Chlorophyll, ribosomes

Modified (Grundon *et al.,* 1997)

Due to high outputs of N from plantations and the possible exhaustion of mineralisable organic N, intensively managed forests usually respond to N applications after the first or

second rotation (Gonçalves *et al.,* 2004; Xu and Dell, 2002) and this is evident on South African forestry sites with low concentrations of soil organic matter (Herbert and Schönau, 1989; Du Toit *et al*., 2010). Laclau (2001) reports that the input-output budgets at the ecosystem level in the Congo, show applications of N fertilizer need to increase over successive rotations to sustain growth of eucalypt plantations. Conversely, Adams *et al.* (2003) state that competition for N was significant for two years after planting in *E. globulus* and not alleviated by high N levels of fertilisation in plantings. It is therefore not possible to finely regulate N availability through fertilisation, especially where rainfall is limiting and weed growth prolific.

Linder (1982) states that differences in mineral nutrient supply, especially N, can change tissue mineral composition, relative to differences in water regimes. Ingestad and Lund (1986) report that tree seedlings grow exponentially for weeks where space and nutrients are conserved. Ontogeny is attained at a predetermined relative growth rate (RGR) through the judicious supply of nutrients. Steady-state exponential growth is controlled by the relative addition rate (RAR) of a key nutrient, whilst other essential nutrients are non-limiting. RAR thus drives RGR, which increases linearly with RAR to a point of nutrient saturation as a species trait. Maximum RGR also depends upon PAR and CO_2, but genetic factors eventually limit growth (Figure 2.9).

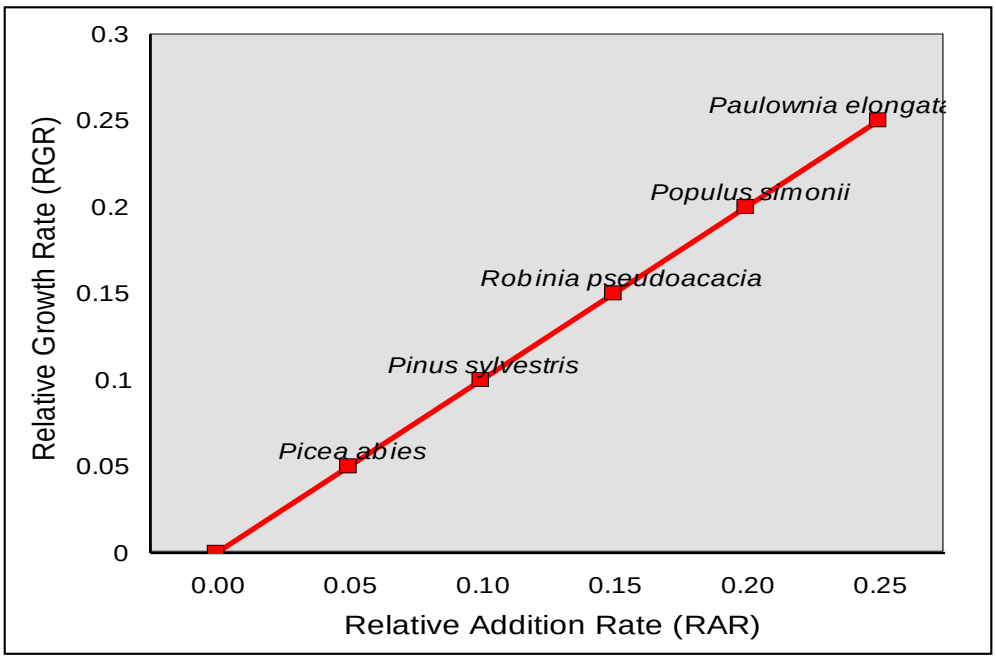

Figure 2.9: Linear relationship between RGR of tree species and the corresponding relative rate at which nutrients were supplied (RAR) (Kriedemann and Cromer, 1996)

The RGR for *E. grandis* seedlings under natural daylight during summer can reach 12% per day, so that values as high as 25% per day are possible with continuous light (Cromer and Jarvis, 1990). The high mobility of N and K dictate that they be evenly spread over soil and concentrations split to balance changes in demand. Although such applications can improve fertilizer efficiency research shows N, P and K applications in plantations that achieve canopy closure in 1.5 to 2.0 years after planting, also achieve high nutrient use efficiency through biogeochemical cycling and are less responsive to further fertilizer applications (Barros *et al.*, 1992; Gonçalves *et al*. 1997).

Fife and Nambiar (1995) report that applications of 600 kg N ha^{-1} to *P. radiata* produced stem wood volumes = 228 m^3 ha^{-1} at 9 years, as opposed to control plots = 178 m^3 ha^{-1}. Further, pre-dawn needle water potential (Ψ) was consistently higher (reduced water stress) in N fertilised treatments than control trees. Interestingly, the water stress integral (S_ψ), decreased with increasing levels of N. Fife and Nambiar (1995) deduced that nitrogen application increased growth rates by improving the nutrient status of trees and lowering water stress in summer. Forrester *et al*. (2010) note that increased N, combined with P availability, can increase instantaneous leaf-level water use efficiency (WUE) through greater photosynthetic capacity without a proportional increase in transpiration or stomatal conductance.

Phosphorus (P)

Phosphorus is essential as a structural element of nucleic acids, phospholipids and phospho-proteins and important in regulation of key enzymes (Table 2.3). Carbohydrate biochemistry and transport are particularly affected in deficient plants. Phosphorus readily moves from old to young leaves and inner bark to shoot tips (Dell, 1996). Kirshbaum and Tompkins (1990) state that plants receiving inadequate supplies of P show a variety of physiological responses such as increases in the ratio of root to leaf dry weight and a reduction in specific leaf area. Gonçalves *et al.,* (2004) record that low P availability in highly weathered soils of sub-tropical and tropical regions can seriously limit growth. Phosphorus fertilizer applied at planting will endure for most of the rotation in short rotation crops and often have a carry-over benefit into the next rotation (Smethurst and Wang, 1998; Crous *et al*., 2008).

Lacey *et al*. (1966) note that seedlings of *E. grandis* grown under luxury P supply contained 0.32% P in leaves and roots, whilst O'Connell *et al*. (1978) report that levels for mature leaves of field grown eucalypts were 0.5% P. According to Wallace *et al*., (1986), the application of Zn alleviate symptoms of excess P concentrations in mature leaves. Zn

deficiencies may enhance P absorption and transport, but conversely may negatively affect P remobilization. Kirshbaum and Tompkins (1990) report carbon assimilation rates for *E. grandis* seedlings raised in controlled environments that ranged from 11.7 $\mu mol^2 s^{-1}$ at low P concentrations to 23.1 $\mu mol^2 s^{-1}$ for seedlings with the highest P status. The critical threshold of available P falls exponentially with plant age, from 37 $mg\ g^{-1}$ for 90 day old seedlings, to 7 $mg\ g^{-1}$ for 150 day old seedlings. Approximately 4 $mg\ g^{-1}$ of P is required at 6 years old to maintain an MAI of 60 $m^3\ ha^{-1}\ yr^{-1}$ in clay rich soils (De Barros and De Novais, 1996). Photosynthetic measurements showed that the CO_2 assimilation rate, together with relative leaf growth rate is sensitive to P nutrition (Kirshbaum and Tompkins, 1990).

The relationship between soil acidity and NH_4^+ uptake correlate to P concentration. *E. alba* seedlings grown in a nutrient solution with NH_4^+ as the only N source exhibited a greater maximum rate of absorption (V_{max} – P) than those grown in a NO_3^- solution. Plants supplied with NH_4^+ absorbed 55% more P than those supplied with plants supplied only with NO_3^- (Vale *et al*., 1984). Soils of low pH and N uptake are enhanced by the predominance of the ammonium form and in turn, P uptake increases (De Barros and De Novais, 1996).

Potassium (K)

Potassium functions in the stabilization of pH and osmo-regulation and is required in the synthesis of proteins and carbohydrates (Table 2.3). It is also acts an activator of numerous enzymes and plays a pivotal role in the control of stomatal opening. In K deficient plants, protein synthesis and photosynthesis are impaired and localized in cells from old leaves (Dell, 1996).

Calcium (Ca)

Calcium is mostly stored in cell vacuoles (calcium oxalate crystals) and cell walls where it is associated with pectin in the middle lamella (Dell, 1996). Calcium oxalate that accumulates in bark to a concentration 20 times that in wood (Pereira *et al*., 1996) is essential for membrane stability and cell division (Table 2.3). Calcium plays an important role in osmo-regulation and the cation-anion balance (Mengel and Kirby, 1982). Anderson (1982) reports that Ca and P affect Fe availability and chlorosis develops in eucalypt seedlings leaves due to the inactivation of Fe at high external levels of Ca. Foliar analysis of severely chlorotic seedlings suggests that high levels of Ca (>500 µg) may have a detrimental effect on iron absorption and metabolism. A balanced K: Ca ratio is also essential for the normal metabolism of green plants and high levels of Ca can have an inhibitory effect on the reactions of respiration and intermediary metabolism (Anderson,

1982). Significant growth responses following fertilization with Ca is only common on sites where exchangeable Ca of the topsoil is lower than 0.4 $cmol_c$ L^{-1} of soil (Rocha *et al*., 2019).

Magnesium (Mg)

A major function of Mg is as a coordinated metal in chlorophyll, protein synthesis, the activation of enzymes and regulation of cellular pH balance (Dell, 1996). In comparing the response of *Nothofagus* seedling to differing concentrations of Ca, K and Mg, Sun *et al*. (2001) report that decreasing rates of Mg reduced growth rates of both shoots and roots, resulting in leaf chlorosis and senescence. Significant growth responses following fertilization with Mg is only common on sites where exchangeable Mg of the topsoil is lower than 0.2 $cmol_c$ L^{-1} of soil (Rocha *et a*l., 2019).

Sulphur (S)

Sulphur uptake of *E. grandis* is highly dependent on the presence of nitrate and phosphate (Ferreira, 1986). It is a major constituent of amino acids cysteine and methionine, and hence protein synthesis is impaired in S deficient plants. Sulphur is required in the production of thiamine, co-enzyme-A and sulfolipids and is not mobile in the phloem. Symptoms of deficiency first appear in young leaves and as leaf chlorosis due to a decline in S chlorophyll (Dell, 1996).

2.15.2. IMPACT OF NUTRIENT LOSS AND ACCUMULATION IN SHORT ROTATION EUCALYPTS

The impact of nutrient losses depends on the total nutrient reservoir, replenishment from aerosol inputs, weathering of subsoil and management practices that aid or hinder incorporation of the nutrient-rich litter, including harvesting of leaves, litter, logs or whole trees. Dynamic sustainability is influenced by the proportion of nutrients lost in relation to the total store, especially considering the unequal concentration of nutrients in plant tissue. Thus, the ratio of nutrient export to nutrient store (stability ratio) is advocated as a key measure of long-term ecosystem stability and any value greater than 0.3 raises serious stability questions in the long term (Evans, 1999). Miller (1995) notes that nutrient removal in forestry cropping systems are typically only one-fifth to one-tenth that of arable farming. The findings of an *E. urophylla* x *E. grandis* hybrid study by Folster and Khanna (1997) at Jari, northeast Amazonia, Brazil, with three different site histories, is summarised below (Table 2.4).

Table 2.4: Nutrient concentrations harvested in stem wood and bark - 54 month old *E. urograndis,* at Jari, N.E. Amazon

Treatment and material	Mass (t/ha)	Total N (kg/ha)	Total P (kg/ha)	Exchangeable K (kg/ha)	Exchangeable Ca (kg/ha)	Exchangeable Mg (kg/ha)
a. Soil		12924	1350	150	1365	253
Wood	109	245	12	154	581	50
b. Soil		3548	1268	45	435	117
Wood	91	204	9	128	452	42
c. Soil		11686	3606	301	13	161
Wood	88	197	10	124	254	40

Treatments: a) First rotation stand. b) Second rotation following first-rotation of 12 years of *P. caribaea.* c) Fourth-rotation stand following three rotations (total 14 years) of *Gmelina arborea* (Folster and Khanna, 1997)

In treatments b and c, exchangeable K and Ca proved to be critical. To quote Folster and Khanna (1997): "*Twelve of the stands were in the second to fourth rotation, indicating that Gmelina, Pinus or Eucalyptus had already extracted their share of base cations from the soil and left it impoverished*". The stability ratio of greater than one suggests a level of unsustainability. Whilst the authors state that uncertainties remain regarding the minimum amount of nutrients required by a stand, they do indicate that 87% of Ca, 48% of K and 68% of Mg uptake by eucalypts is contained in bark and thus preventing this removal can offset deficits. Counter to this, other authors report eucalypt tree growth continuing unhindered on sites where conventional soil analysis indicated significantly depleted Ca levels, further exacerbated by the removal of bark from the site (Evans, 1999). Du Toit and Scholes (2002) argue that a more robust and reliable index of nutritional sustainability should express the net nutrient loss as a fraction of readily available nutrient pools in the soil. Accumulation of nutrients post-canopy closure are mainly due to the production of wood volume as foliage quantities are relatively stable due to self-shading and resource supply (Gonçalves *et al.* (2004). Ryan *et al*., (1997) illustrated that during the post canopy phase, leaf area index (LAI) is constant or decreases for reasons not clearly understood; however, plantation eucalypts are generally harvested before age related decreases in LAI become noticeable.

2.15.3. NUTRIENT RETRANSLOCATION FROM LEAVES, WOOD AND BARK

Fife and Nambiar (1984) record that most information on retranslocation of nutrients in eucalypts emanates from senescent leaves, yet studies of other forest species suggest there may be significant retranslocation of nutrients from young foliage and fine roots (Table 2.4). Grove *et al*. (1996), Specht and Groves (1996) report that the proportion of N and P remobilized from senescing leaves is greater in eucalypts than annual crop species. The increased uptake of nutrients through fertilization can increase N and P concentrations in the stem, but greatest variation in eucalypts is located nearest the cambium and it is most

likely that increased P storage is in a readily mobilized form (Mulligan, 1988). When N and P uptake exceed short-term requirements, due to seasonal conditions or short-term fertilizer effects, the reservoir of nutrients in the stem may be important to sustain growth (Grove *et al.*, 1996). In eucalypts, the retranslocation of nutrients from the outer bark is a significant component of biochemical cycling. Average concentrations of nutrients are often much greater in bark than stem-wood and although bark constitutes less than 30% of stem biomass, it contains a larger proportion of the total nutrient content (Table 2.5) (Beadle and White, 1968, Lambert, 1981b).

Table 2.5: Nutrient concentration (%) and withdrawal. Remobilization of nutrients from eucalypt leaves prior to litter fall. Nutrient withdrawal calculated as % concentration change between green (G) and freshly senescent leaves (S)

Species	Leaf stage	N	P	K	S	Ca	Mg
E. diversicolor	G	1.17	0.06	0.92	0.11	0.82	0.28
	S	0.61	0.02	0.25	0.09	1.09	0.28
Nutrient withdrawal		48	64	73	19	-33	0
E. marginata	G	0.84	0.04	0.57	0.10	0.58	0.43
	S	0.30	0.01	0.26	0.09	0.74	0.40
Nutrient withdrawal		64	78	54	28	-28	7
E. regnans	G	1.52	0.12	1.13	-	0.23	0.25
	S	0.33	0.04	0.29	-	0.56	0.20
Nutrient withdrawal		78	70	74	-	-144	20

(Modified - GROVE *et al.,* 1996)

Changes in nutrient concentrations from mature green leaves to freshly senescent leaves provide only an approximation of nutrients remobilized from foliage and contributing to tree growth through internal nutrient cycling. These estimates do not adequately account for increased sclerophylly and consequent dilution of nutrients with leaf maturation or for the variation in nutrient content with ontogeny and seasonal fluctuations in nutrient uptake (Maggs, 1985). Concentrations of mobile nutrients within leaves depend primarily on the net effect of inflow of xylem and efflux through the phloem (Hill, 1980). Variable yet large gains in Ca concentrations between mature, senescent leaves of eucalypts suggest that age and structural constituents differ widely. The proportion of nutrients remobilized during leaf senescence depend on relative mobility within the phloem and initial nutrient concentration (Loneragan *et al*., 1976; Chapin and Kedrowski, 1983). Woodwell (1974) states that mobile nutrients in hardwoods increase rapidly during leaf expansion, reaching a maximum early in the life of the leaf. In contrast, immobile nutrients such as Ca accumulate throughout the life span.

A major component of eucalypt biochemical cycling is the withdrawal of nutrients from bark and wood during the transition from sapwood to heartwood. An essential difference in leaf nutrient retranslocation is that phloem-immobile elements, such as Ca, translocate radially in the stem during heartwood formation from the outer bark to growing tissue; however, in leaves, Ca remains in senescent tissue. Lambert (1981b) reports the retranslocation of Ca from heartwood varies markedly on different sites. Concentrations of Ca in *E. obliqua*, across a range of sites, may decrease tenfold from sapwood to heartwood but not vary through the stem wood at others. Marschner (1999) states that the mechanisms for Ca retention and remobilization in the stem are not well understood; however, exchange adsorption is important in long distance Ca transport and may explain why movement is not directly related to rates of water transport.

Grove et al. (1996) state that eucalypts are particularly efficient in retranslocating P from wood during heartwood formation. Nutrient concentrations are greatest near the cambium and whilst there are strong gradients from the outer-wood to the inner-wood, gradients from the inner-bark to the outer-bark are more variable with nutrient concentrations in the heartwood of eucalypts generally low (Grove *et al.,* 1996). Concentrations of other nutrients also decrease with transition from eucalypt sapwood to heartwood. Gradients for K are often as large as P, whilst limited data indicates a smaller variation for N (Beadle and White, 1968; Hingston *et al*., 1979, Lambert, 1981b). The concentration of Ca decreases from sapwood to heartwood in many but not in all eucalypts (Table 2.6).

Table 2.6: Concentration (%) of nutrients in sapwood, heartwood and bark of selected eucalypts. Heartwood (H), Sapwood (S), Bark (B)

Species	N			P			K			Ca		
	H	S	B	H	S	B	H	S	B	H	S	B
E. saligna	0.120	0.200	0.300	<0.001	0.008	0.020	0.006	0.075	0.440	0.025	0.064	3.880
E. maculata	0.100	0.180	0.270	<0.001	0.005	0.011	0.022	0.080	0.190	0.237	0.124	2.930
E. diversicolor	0.070	0.120	0.130	0.001	0.008	0.007	0.018	0.105	0.145	0.018	0.064	0.310
E. grandis	0.150	0.310	0.240	<0.001	0.013	0.012	0.020	0.125	0.175	0.075	0.065	3.150
E. marginata	0.050	0.100	0.210	<0.001	0.005	0.012	0.023	0.051	0.234	0.007	0.024	0.430
E. viminalis	0.090	0.200	0.270	0.014	0.016	0.020	0.007	0.115	0.160	0.020	0.073	2.240

(Modified – Grove *et al.,* 1996)

2.15.4. NUTRIENT UPTAKE BY ROOT SYSTEMS

Nutrient content and reaction of nutrient ions within soil determine nutrient availability. The absorptive capacity of roots limit the uptake of relatively mobile nutrient ions (e.g. NO_3^-, SO_4^{2-}, Ca_4^{2+}, Mg^{2+}) that move to roots through mass flow. However, for nutrient ions that react with soil minerals and organic matter and that are generally less mobile (e.g. $H_2PO_4^-$, NH_4^+, Zn^{2+}, Cu^{2+}), diffusion is the rate limiting step. Concentrations of immobile ions in soil solution are affected by clay and organic matter whilst phosphate also reacts strongly with the surfaces of Fe and Al oxides. For these ions, depletion zones develop around roots over short periods. In low nutrient environments, absorption of nutrients is determined by rooting density and other properties of root surfaces (Grove *et al.,* 1996). A contributing factor to low absorption rates of eucalypt seedlings is the diversion of assimilates to root production thus ensuring seedling survival. The early growth of *Eucalyptus regnans* seedling is characterized by the initial development of a deep taproot with extensive lateral roots developing later (Grove *et al.,* 1996).

Roots are most abundant in soils where organic matter and nutrients are concentrated. Grove *et al.* (1996) estimate a rooting density (root length per unit volume of soil - L_V) of 7 cm cm^{-3} in the top 10 cm of soil for *E. marginata* and an L_V = 2 cm cm^{-3} for *E. regnans and E. grandis*. The latter low root densities maybe ascribed to a higher nutrient supply. The effective root length is generally greater for species with fine roots than coarse roots. A number of eucalypts utilize fine root hairs to increase the volume of soil from which nutrients can be absorbed. Auto-radiographic studies illustrate that the depletion zone for P and Zn in strongly fixing soils correspond with the volume occupied by root hairs. Within eucalypts, root hairs continually slough off following the development of ectomycorrhizae, enhancing the absorption of water and poorly mobile nutrients in infertile soils. Fine root turnover ensures the maintenance of a small, fine root biomass and minimizes respiratory losses from ineffective roots (Grove *et al.,* 1996).

2.15.5. SEASONAL VARIATION IN NUTRIENT UPTAKE OF EUCALYPTS

Eucalypts take up nutrients mostly from surface soil where fine roots and mycorrhizae are abundant and nutrients concentrated. Seasonal fluctuations in surface soil moisture and temperature exert a strong effect on nutrient uptake by roots, especially in areas with strong seasonal variation (Grove and Malajczuk, 1992). The eastern part of subtropical South Africa is a good example and constitutes the greatest portion of local commercial timber plantations. The periodicity of fine root growth and restricted period of nitrogenase activity in nodules of eucalypt forest legumes suggest that much of the annual uptake of nutrients

is in spring and early summer (Dell and Wallace, 1983). Significant seasonal variation of nutrient concentrations in eucalypt foliage are recorded, although such trends have not been examined in terms of nutrient uptake, root activity or variations in soil moisture and temperature, as in other evergreen tree genera (Schönau, 1981; Bell and Ward, 1984). Increased concentrations of N in foliage of six-year-old *E. saligna* and *E. wandoo* have been observed in spring, corresponding with the period when fine root development and microbial action are highest (Dell and Wallace, 1983).

2.15.6. NUTRIENT DISTRIBUTION, STORAGE AND SUPPLY

There is little information pertaining to the distribution and storage of inorganic and organic forms of nutrients in eucalypts, particularly N (Grove *et al.,* 1996). Mulligan (1988) states that differences between nutrients in their distribution are linked to physiological functions and relative mobility within the plant. Studies indicate that root systems of eucalypts are extensive and contain a greater proportion of total nutrients in environments where either nutrients or water supply limit growth. A greater allocation of assimilates and increased proportion of nutrients retained in roots is a common response to low nutrient supply in species growing under stress (Clarkson and Hanson, 1980). In seedlings of *E. pilularis*, a P deficiency increases the retention of P and allocation of carbon (C) to roots at an early stage in development. Subsequent increases in P uptake are attributed to the formation of ectomycorrhizae resulting in increased transfer of P to shoots and increased leaf growth (Mulligan and Patrick, 1985).

Variation in the supply of nutrients due to differences in soil nutrient status affect the distribution of nutrient between tree components. Increased nutrient supply alters distribution by preferential accumulation of nutrients in specific sinks or indirectly through growth and the partitioning of dry matter. Increases in the external supply of N or P to young seedlings of *E. grandis* decreases the root dry mass relative to leaves, although partitioning of dry matter between leaves and stems is not affected (Cromer and Jarvis, 1990). Growth response of eucalypt seedlings to the application of P are generally associated with increased P concentrations throughout the plant; however, P concentration are greater in stem tissues, particularly bark, as opposed to leaves (Grove *et al.,* 1996). In recoppiced *E. diversicolor*, SW Australia, the application of P increased concentrations of P in all above ground components, but was proportionally higher in twigs, bark and stem wood than leaves. The application of N also increased concentrations of N in plant tissues but increases in woody tissues were less marked than for P (Grove, 1990).

2.15.7. THE INFLUENCE OF THE FOREST CANOPY ON NUTRIENT CYCLING

Prescott (2002) states that the availability of nutrients in a forest ecosystems depend on efficient recycling and decomposition rates, and nutrient mineralization is governed by temperature, moisture conditions and chemical and physical nature of litter. The forest canopy has a major influence on nutrient cycling, especially through the leaf litter source. Shading and insulation afforded by the canopy buffers extreme temperatures at ground surface and moderates hydrological conditions by redirecting precipitation and manipulating soil water through transpiration. Hydrological alterations also impact on the magnitude of nutrient loss through leaching or overland flow. Prescott (2002) reports that such processes increase or decrease concentrations of macro nutrients, and foliage and branches, although comprising a relatively small portion of total tree biomass, constitute major nutrient sinks of up to 50% of immobilised N, P, Mg, K and Ca of tree biomass. Canopy characteristics determine the quantum and composition of leaf litter produced, which largely determines the amount of nutrients to be recycled, the composition of soil microbial and faunal communities, and the resulting availability of nutrients.

The removal of canopy biomass during harvesting is associated with several changes in nutrient cycling, including the death and decay of roots, and changes in aboveground vegetation cover. Clear-cut harvesting is followed by a period of increased soil nutrient availability, but losses also follow through leaching, increased rates of N mineralization and nitrification. These effects usually begin within a few months of clearfelling and last for 3-5 years, although the intensity and period of the effect vary according to site fertility and climate. This phenomenon can be attributed to factors such as:

1. Decline in nutrient uptake by vegetation due to clearfelling of the standing crop.
2. Increased rates of decomposition of residual organic matter resulting from warmer and moister conditions.
3. Reductions in C inputs from litter and root exudation, leading to a decline in N assimilation by microbial biomass.
4. Decay of logging debris, foliage, woody material and roots (Prescott, 2002; Dovey *et al.* 2014).

Empirical evidence seldom confirms that rapid decomposition, post clear felling, is responsible for a flush of nitrates (Prescott, 2002). Conversely, reduced concentrations of available C and increasing nitrate availability in clear fellings has gained credence, and is now hypothesized that the cessation of annual input of canopy litter, and resulting reduction in labile C, causes microbial biomass to be C-limited rather than N-limited (Prescott, 2002).

This in turns leads to reduced assimilation of nitrate (NO_3^-) and a flush of available (NO_3^-) characteristic of clear felling. It can thus be argued that the canopy plays an important role in retaining nutrients (especially N) on site by storing nutrients in foliage and through the steady input of available C in litter (Prescott, 2002). However, there are exceptions, i.e. sandy soils in moist, warm climates with rapid decomposition and low anion exchange capacity. Dovey *et al*. (2014) report nitrate leaching (kg/ha over 12 months) to increase from < 1 kg ha^{-1} (standing crop) to 16.6 kg ha^{-1} (clear-felled crop), to 31.0 kg ha^{-1} (clearfell and burnt slash) in Zululand. Clear felling and residue management governs the rate of nitrate leaching, specifically in warm climate sites with low anion exchange capacity. Although 31 kg ha^{-1} of leached N is not substantial over a whole rotation, it is still a sizeable mass for that first 12-month period after clear felling, considering that inputs through atmospheric N deposition is in the order of 10 – 15 kg ha^{-1} per annum (Dovey *et al*., 2014).

2.15.8. BIOMASS AND NUTRIENT POOLS IN EUCALYPT PLANTATION SYSTEMS

In the ICFR Karkloof study, above ground eucalypt stand biomass equated to 135 t ha^{-1} (Du Toit, 2003), whilst other reports for *E. grandis* and eucalypt hybrids varied from 52 - 196 t ha^{-1}. As tree stands mature, the portion of above ground biomass in the crown decreases relative to stem wood from approximately 30% at 5 years to 10% at 12 years (Bradstock, 1981). The Karkloof study showed a larger proportion of biomass within the crown but final stand density (1461 stems ha^{-1}) was a contributor. Average tree size was relatively small (7 years), with stem biomass = 91 t ha^{-1}, with other studies ranging from 30 - 147 t ha^{-1}. Nutrient content of the non-utilizable fraction of above ground biomass (crown plus bark) are presented (Table 2.7). This study emphasized the importance of limiting timber harvesting solely to utilizable timber, to minimize nutrient losses, and must be a consideration in the compilation of all residue management practices (Du Toit, 2003).

Table 2.7: Nutrient content percentage contained in biomass - Karkloof study

Component	N %	P %	K %	Ca %	Mg %
Above ground	68	54	70	80	82
Forest floor	53	33	12	30	12

(Modified – Du Toit, 2003).

Du Toit (2003) reports that root and stump biomass measured at Karkloof amounted to 69.5 and 15.2 t ha^{-1} respectively and were high due to three successive coppice rotations. Previous studies record root mass from 13 - 46 t ha^{-1} with coppice showing greater root mass than planted crops. Root biomass represents a large store of nutrients (especially N, P and Ca) not affected by harvesting and site management.

The forest floor biomass at Karkloof equated to 70 t ha^{-1} whilst forest floor loading in tropical systems rarely exceeds 20 t ha^{-1} and 100 t ha^{-1} in temperate forests (Du Toit, 2003). The decomposition rate of organic matter of a forest floor is affected by several factors of which moisture and temperature are major roles. The Karkloof study, very similar in terms of soils and climate to the Mountain Home trial series was characterised by relatively low winter temperatures and extremely low rainfall for 5 months. These conditions certainly contribute to a build-up of forest floor mass with relatively large immobilisation of N, P and Ca that temporarily prevented from cycling back into the system (Table 2.7).

2.15.9. NUTRIENT CAPITAL AND THE IMPACT OF SITE MANAGEMENT

Nutrient losses due to burning depend strongly on fire intensity and quantity of fuel consumed (Du Toit, 2003). Fire intensity can be broadly categorised by the degree of forest floor consumed by fire. A high intensity fire will consume all above ground litter whilst a medium intensity fire will burn most of the undecomposed (L) and some of the humus (H) layer. A light intensity fire will scorch, but not consume the H layer and most residue burns applied to short-rotation eucalypt crops in South Africa are a medium intensity type (Du Toit, 2003).

Du Toit (2003) records an estimated loss of N through burning (440 kg ha^{-1}) as constituting 42% of the N pool in a regular eucalypt slash/residue load, whilst Morris (1986) calculated a loss of 1183 kg N ha^{-1} (54% of the slash N pool) with a high intensity fire in *Pinus patula* residues. This outcome supports the principle of increasing N losses with rising fire intensity. The average burning loss of N per rotation in a eucalypt 'plant +2' coppice, estimated at 150 kg N ha^{-1} (Table 2.8), was larger than N losses through round wood harvesting. Although combined N losses through harvesting and residue burning (± 250 kg N ha^{-1} per rotation) only constitute 1% of the total N pool in the system (Table 2.8), the combined decrease of plant available N pool was estimated at 13%. Despite N losses being well buffered by large N soil pools, the deficit through residue burning and harvesting cannot be totally replaced by current fertilization practices and an input-output budget showed an overall net N loss in a "plant +2" regime, including slash burning, to be moderately small (± 10 kg N ha^{-1} a^{-1}) (Du Toit, 2003).

Table 2.8: Effects of management operations on the nutrient capital in various pools of the system. Mean values for slash loads within the same column followed by different letters are significantly different ($p < 0.05$)

Treatment/operation	Mass	N	P	K	Ca	Mg
	All values in kg ha $^{-1}$					
Slash loads						
Double slash	153200[a]	1378[a]	67[a]	275[a]	1413[a]	286[a]
Regular slash	116527[b]	1044[b]	53[b]	193[b]	**823[b]**	**201[b]**
Burnt slash	31415[c]	604[c]	27[c]	96[c]	747[c]	151[c]
Management removals						
Utilizable stem wood	90604	101	13	67	63	19
(% of the available pool)	n.d.	5	**15**	8	4	**2**
Losses through slash burning	85112	**440**	**26**	**97**	76	**50**
Average effect of burning 1 in 3 cycles	28371	**147**	**9**	32	25	**17**
(% of the available pool)	n.d.	7	**10**	4	1	**2**
Management additions						
Additional slash	36673	334	14	82	590	85
(% of total pool in system)	n.d.	17	17	9	33	8
Fertilization	151	17	33	0	**1**	**2**
(% of total pool in system)	n.d.	**1**	39	-	<1	<2

n.d. = not determined (**Bold font = highlighted in text**) (Du Toit, 2003)

Du Toit (2003) reports approximately 26 kg P ha^{-1} lost through residue burning at the Karkloof study (Table 2.8) constituting 49% of the P pool contained in residue. The removal of 13 kg P ha^{-1} and 9 kg P ha^{-1} through harvesting and residue burning amounts to 15% and 10% of the estimated available P in the "plant +2" system. The inherently low available P status of highly weathered soils in the KZN Midlands, coupled to a substantial portion of P removed through harvesting and/or slash burning, appears to be the main reason for the consistent response to P fertilization (Du Toit, 2003).

A relatively large soil pool exists for K (466 kg ha^{-1}) and up to 258 kg ha^{-1} is held in non-utilized pools (forest floor + tree crown + bark). In contrast to Ca and Mg, K is easily lost from residue through leaching; however, the bulk of the leached fraction remains in the soil pool whilst losses through residue burning were close to 97 kg ha^{-1} (38% of initial K pool in residue). The average loss of 100 kg ha^{-1} per rotation in the 'plant+2' regime, through burning and round wood harvesting is concerning as recommended fertiliser blends contain

either zero or low concentrations of K due to its variable economic growth responses (Du Toit, 2003).

Available Ca pools in the Karkloof soils were 742 kg ha^{-1} whilst Ca contained in conventional residue loads can be as high as 823 kg ha^{-1} and constitute a substantial fraction of available Ca. Low intensity fires have a minor impact on Ca pools due to its stability at high temperatures. Harvesting of stem wood and residue burning revealed a small effect on the Ca pool ('plant+2 system) with a combined loss per rotation of 89 kg ha^{-1}. Removal of bark (109 kg ha^{-1}) or partial removal of harvesting residue through firewood collection would have a much greater impact on Ca on the system than wood harvesting. Although simple to augment, Ca levels are not optimised under current fertilizer regimes where highly concentrated fertilizer sources (ammonium phosphates) are preferred to super phosphates or rock phosphates, both containing substantial concentrations of Ca (Du Toit, 2003). The Karkloof trial revealed the highest concentration of Mg in the soil pool (771 kg ha^{-1}), with 1030 kg ha^{-1} for the total system. In contrast to high Ca levels, the Mg pool post harvesting contained only 201 kg ha^{-1}, with 50 kg ha^{-1} lost to burning. Under the 'plant+2' treatment round wood harvesting and burning removed 19 and 17 kg ha^{-1} of Mg per rotation respectively, less than 2% of the system pool and thus the Mg pool is well buffered against losses through burning or harvesting by virtue of the large soil-available pool (Du Toit, 2003).

The resilience of a system depends to a large degree on the net flux in relation to the size of the bio-available pool. Where nutrient pool sizes are large, the system buffers against short-term losses. Many fluxes vary spatially and temporally and with respect to the intensity of land practices. With small nutrient pools, variability in fluxes (influx or efflux) will cause large variations in system stability whilst in contrast, a large nutrient pool will mean that variation in the net nutrient flux will have a less pronounced impact on the stability of the system, resulting in easier management (Du Toit and Scholes, 2002).

2.15.10. THE BIOCHEMICAL CYCLE AND ANNUAL NUTRIENT REQUIREMENTS OF SHORT ROTATION EUCALYPTS

According to Grove *et al*. (1996) eucalypts show differences in Ca concentrations between heartwood and sapwood and between inner and outer bark. Remobilization of Ca within stems and branch tissue is a major source of Ca to complement new short growth, particularly where uptake of Ca by fine roots is limited by seasonal drought. In mature *E. obliqua* and *E. grandis*, 45 - 55% of annual P and 33% of annual N requirements are

obtained from biochemical cycling (Turner and Lambert, 1983; Baker and Attiwill, 1985). In *E. obliqua,* 25% of annual K and Mg, but only 2% of Ca requirements are through internal redistribution *(*Attiwill, 1980). The low redistribution of Ca indicates that *E. obliqua* must depend on a continuous uptake of calcium from soil to meet new shoot growth synthesis; however, Turner and Lambert (1983) report no net redistribution of Ca in *E. grandis*, although remobilization from bark and heartwood amount to 22% of gross annual Ca requirements.

Retranslocation of nutrients from eucalypt foliage is a major component (45-92%) of the biochemical cycling for N, P and K (Attiwill, 1980; Turner and Lambert, 1983). Redistribution of these nutrients during the transition to heartwood is also a significant component of biochemical cycling, whilst redistribution from the outer bark and twigs are low. The retranslocation of nutrients from stems is thus less significant during biochemical cycling than from foliage, although the extent of nutrient storage and retranslocation in bark, branches and twigs is generally under estimated (Grove *et al.*, 1996). Attiwill (1980) in a summary of data from a range of forest ecosystems showed that hardwoods, including eucalypts, retain a greater proportion of their annual uptake of P than conifers (Table 2.9). This high retention and the generally low overall P content of eucalypts indicates effective mechanisms for conserving and utilizing absorbed P.

Table 2.9: Comparison of the annual retention of nutrients by forest species. Uptake is defined as retention plus the amount of nutrient in the biochemical cycle

	P	K	Ca
Pines	0.19	0.19	0.16
Other conifers	0.18	0.30	0.16
Hardwoods	0.42	0.35	0.40
E. obliqua	0.34	0.23	0.17

(Modified – Attiwill, 1980)

Data suggests that nutrient-use efficiency for wood production is a consequence of two sets of interacting processes, assimilation and partitioning, both of which are nutrient sensitive. Positive effects of increased nutrient supply on assimilation by leaves are compounded by an increase in stem growth with relatively less root growth and turnover (Kriedemann and Cromer, 1996). The combined effect of a number of mechanisms that enhance the acquisition and conservation of nutrients enables eucalypts to endure quite infertile soils and the efficiency of inherent mechanisms responsible for the uptake and utilisation of nutrients is undoubtedly a major reason for the success as a plantation species on nutrient-poor sites. Many eucalypts have the potential for rapid growth and storage of nutrients when

fertilized with N and P, indicating a considerable plasticity within the genus to adjust to changes in nutrient supply (Grove *et al*., 1996).

2.16. THE ROLE OF SITE PREPARATION

Land preparation at establishment is critical in terms of transplant survival and rapid canopy closure. Currently, 85% of eucalypt plantations in Brazil are established utilising minimum cultivation, which prescribes the retention of plant residues followed by soil preparation. Soil preparation can mitigate limited water resources by reducing runoff and increasing effective soil depth where there are physical impeding layers (Gonçalves *et al*., 2017).

Site preparation to improve growing conditions includes the treatment of harvest residue (burning, spreading, mulching or chopper rolling), soil tillage (ploughing, ripping) and pitting). Reported tree growth responses to residue management and soil tillage are variable (Rolando *et al*., 2002; Gonçalves *et al*., 2004). The drive to reduce soil erosion and costs has led to a renewed focus on minimum site cultivation, including litter retention, the benefits of which include reduced nutrient and organic matter loss, and the protection of important soil physical properties (Gonçalves *et al*., 2004). The retention of harvest residues increases eucalypt productivity at different levels, with respect to water and nutrient availability and the maintenance of critical soil properties such as porosity, root growth, infiltration and aeration (Gonçalves *et al*., 2002; Stape *et al*., 2002; Xu and Dell, 2002).

Gonçalves *et al*. (2004) report ripping from 20 cm – 100 cm deep to be a common practice in Australia and requires considerably more powerful machines than for surface cultivation. Deep ripping has been implemented for decades under the assumption of improved tree growth (Figure 2.10); however, Holz *et al.*, (1999) report no benefit, other than incurring high establishment costs. Ripping and subsoiling have yielded erratic responses in South African soils and its application is site-specific (Smith *et al.*, 2000; Du Toit *et al.*, 2010). .

Figure 2.10: Savannah Eco-Til subsoiling unit mounted on CAT D6 dozer, KZN Midlands, South Africa. Promising operational results on cross slope ripping up to 18% incline have been achieved in terms of erosion mitigation and run off ingress

E. nitens grown on strongly aggregated clay soil, showed a 71% reduction in primary root length as penetrometer resistance (measure of soil compaction/strength) increased from 0.4 to 4.2 MPa, even though water and nutrient availability was maintained and lower mechanical resistance allowed for better radial and longitudinal root growth (Misra and Gibbons, 1996). Gonçalves *et al*. (2004) note that by reducing bulk density through cultivation of the planting hole or through strip cultivation, root growth increased, with an expected increased uptake of nutrients and water. High early growth rates of seedlings benefitted from this ability to absorb nutrients and water, especially when in competition with weed vegetation. Fisher and Binkley (2000) conclude that exposure of mineral soil, elimination of competing weeds and improving water availability must be the primary roles of soil preparation.

2.16.1. RESIDUE MANAGEMENT IN SHORT ROTATION PLANTATIONS

Harvest residue management is dependent on company policy, previous crop, site sensitivity, steepness of terrain and financial constraints. Numerous methods exist to make harvest residues more manageable, including broadcasting of slash, stacking in windrows, burning and mechanically reducing through chopper rolling or mulching (Rolando, 2005). The management of harvest residue is expensive and is usually managed through burning, irrespective of soil sensitivity to erosion (Norris, 1992).

Early establishment mortality in South African plantations continues to plague silviculture with a concomitant negative impact on survival, growth and uniformity, and ultimately the volume of utilisable timber at full rotation. Studies on pines and eucalypts have shown significant growth responses through residue retention (Tutua *et al*., 2008). Although operationally contentious, harvest residues represent an important asset to forestry sites and retention has long-term site sustainability benefits in terms of soil moisture, lowered soil surface temperatures and improved nutrient recycling. As residues hinder access and are in no doubt a serious fire hazard, felled compartments in South Africa are generally burnt in an attempt to reduce the fuel load. Gonçalves *et al*. (2008) report that harvesting systems and level of mechanisation have a major influence on the distribution of residues and the impact on soils can be quite distinct.

Organic matter can also act as a buffer against compaction (Jakobsen and Graecen (1985). Gonçalves *et al*. (2008), Stape *et al*. (2002) report that under water and nutritional stress, residues retained on certain sites can increase nutrient availability. This is strongly associated with reduced nutrient and organic matter losses, and the maintenance of important soil physical properties, i.e. porosity, permeability, infiltration and aeration. Du Toit (2003) reports that plantation management operations carried out during the inter-rotational period (harvesting, residue management and certain silviculture operations) have a major impact on the productivity and long-term sustainability of forest stands, especially where short rotations are applied. Gonçalves *et al*. (2008) state that until the late 1980's, Brazilian residue management closely resembled South Africa, namely windrowing and burning, irrespective of climate and soil type, and believe that the two greatest advances in Brazilian forestry were the abolition of residue burning and adoption of minimum tillage techniques. However, the Brazilian definition of minimum tillage is debateable as their strip cultivation operations most certainly result in the inversion of soil horizons.

After a burning event, increased precipitation can result in nutrient loss through leaching and surface movement with the soil surface physically exposed to the damaging erosive forces of wind and runoff. When soil reaches high temperatures, soil organic matter is destroyed leading to a degradation in soil structure and greater induced susceptibility to erosion (Hendrick, 1979). Nitrogen and sulphur oxidise and volatilise as gases when temperatures exceed 300 ^{o}C (Binkley, 1986) and smoke, known to contain large volumes of nutrient rich ash. Consequently, the South African approach to residue management should be to burn only where essential and to adopt residue management practices that are both economical and environmentally sustainable. Rolando and Little (2004) state that

water and heat stress are often the cause of early tree mortality and any intervention aimed at alleviating water stress, including residue management, must be considered.

A further negative response to residue burning is water repellency, resulting in soils that resist wetting due to the formation of hydrophobic substances of organic origin (Scott, 1991). Soils on which eucalypts have grown for multiple rotations are particularly prone to repellency as a direct result of wild fires or hot residue burns (De Bano, 1981; De Byle, 1973; Scott, 1991). Topsoil of water repellent soils can remain dry, even after rain, resulting in higher mortalities of young plantings and potential reduction in productivity of successive rotations as repellency levels increase. This can cause reduced moisture infiltration and increased overland flow (De Bano, 1981).

Intense fires to burn residue windrows should be limited as it can have a much greater negative impact on nutrient cycling than a harvest operation. However, on resilient sites where excessive residues have accumulated, a controlled burn can be applied when soil conditions are moist Binkley, 1986). McKee (1982) counters that in the short term; controlled burns may enhance the soil status of the major plant nutrients. Such increases may not always be beneficial as nutrient uptake is reduced after harvesting and nutrients lost to the ecosystem through leaching. Gonçalves *et al*. (2008) also notes that burning of harvest residue can result in improved early tree growth, emphasizing the higher initial availability of nutrients released through burning and mineralisation. The same authors do express concern though that burning can result in undesirable effects such as the loss of nutrients through volatilisation, leaching and erosion in the long term. On nutrient deficient sites, such losses could take many years to replenish.

2.16.2. MULCHING IN EUCALYPT PLANTATIONS

The mechanical reduction of harvest residues on an extensive scale is an expensive process and the justification for practices such as mulching must be considered in terms of site sustainability and economic benefits. Although generally accepted that mulching is beneficial to the site, peer-reviewed studies supporting actual gains in survival, growth and uniformity of eucalypt plantings are scarce. Mulching is an important establishment practice in hardwood plantations in subtropical Australia (Huang *et al*., 2008) and practiced on an increasing scale in South Africa. Huang *et al*. (2008) state that mulch is beneficial to forest plantations through improved soil moisture conservation over extended periods. The benefits of mulch are also attributed to changes in soil nutrient availability (Buerkert *et al*., 2000), reduced soil temperature through shading and reduction in raindrop impact (Salau

et al., 1992). In terms of nutrient availability, Huang *et al*. (2008) note that *in situ* N mineralization dynamics during the first year following the application of mulch exacerbates N stress by immobilization, with the 0 - 10 cm layer of soil showing the lowest N availability. In contrast, P became more available under the mulched residue.

Huang *et al*. (2008) state that the effect of mulch on growth of forest plantations has been studied for a number of species and soils, however, our understanding of the physiological mechanisms underpinning the growth response to mulch in hardwood plantations remain limited. Additionally, the effect of mulch on tree growth varies with soils, taxa, microclimate and mulch type. Gonçalves *et al*. (2008) indicate that different soil preparations and residue management treatments have a pronounced effect on the growth of *E. grandis*.

A trial in São Paulo State, Brazil, showed that treatments in which all residues were either retained on the soil surface, incorporated into the soil or burned all showed similar growth at 6.4 years (Gonçalves *et al*., 2008). The removal of bark and slash was associated with a 14.5% reduction in volume (40.5 $m^3 ha^{-1} yr^{-1}$) compared to treatments where residues were retained. The removal of all residues resulted in a 37% decrease in stem volume. It is quite clear that removal of residues on low fertility soils will result in significant volume decreases. Where residues are preserved or the under storey and litter are retained, soil temperature and soil water fluctuations are lower, mean water content of soil is higher and surface temperatures lower than where residues are removed or burned (Gonçalves *et al*., 1999; Gonçalves *et al*., 2008). Du Toit *et al.* (2000) report similar results for water content in South African trials. However, results do indicate that early growth gains are not necessarily expressed at final rotation.

South African commercial forestry still practices controlled burning of harvest residues on a broad scale as a means of countering the ever-increasing threat of arson fires, for access by silviculture and harvesting equipment, and as a cost effective tool to remove the residue. Soil form and slope are major indicators of site sensitivity and well researched locally. Models indicate that up to 50% of planted timber sites along the eastern seaboard of South Africa should not be burnt, although this is impractical on a commercial scale due to the threat of fire (Table 2.10).

Table 2.10: Areas in a South African forestry company, SE Mpumalanga, suited to burning and no burning of harvest residues. Suitability based on soil type, texture, organic matter, sensitivity to erosion and slope

Area	No Burn	Burn	Total	% No burn
Iswepe	15,597	11,925	27,522	57
Piet Retief	14,025	10,015	24,040	58
Dumbe	9,306	11,197	20,503	45
Total	38,928	33,137	72,065	54

Gonçalves *et al*. (2008) report that residue management practices, including burning of slash and the removal of wood and bark in Brazil had the highest impact on nutrient depletion where N and K availability fell below critical levels, beyond the third rotation. In South Africa, of the top 10 geologies in the summer rainfall zone, 60% are sedimentary, 30% granitic (acid igneous) and 10% basic igneous (Smith *et al*., 2005). Higher fertility is attributed to a combination of factors: (1) the prevalence of igneous parent material (± 40%), (2) that portion in the basic and ultrabasic categories (± 10%), and (3) lower leaching in South Africa brought about by high evapotranspiration demand and relatively low rainfall. It is imperative that we do not apply a direct copy of Brazilian silviculture practices to the local South African situation, as there are significant differences in soil form, soil fertility, site resilience and most importantly, rainfall. Due to the slow rates of decomposition, the release of soil nutrients for young seedlings is vitally important. Bouillet *et al*. (2000) indicate that the presence of varying quantities of litter and logging residues affect eucalypt productivity and is largely dependent on localised water and nutrient availability (Table 2.11).

Table 2.11: Response of fast growing eucalypts to residue retention under different climatic and soil conditions

Country and region	Species	Climate	Water supply	Soil fertility	Potential productivity	Response to residue retention
Congo	*Eucalyptus* hybrids	Sub-equatorial 1200 mm. 22 - 27 °C	High seasonal deficit	Very low	Low < 15 t ha^{-1} yr^{1}	No effect (12 months)
South Africa (NE)	*E. grandis*	Cool temperate 850 mm. 3 - 25 °C	Medium seasonal deficit	Very low	Medium 20 t ha^{-1} yr^{1}	Increased growth with increasing residue (8 months)
Brazil (SW)	*E. grandis*	Sub-tropical 1500 mm. 16 - 24 °C	Low seasonal deficit	Very low	High ±40 t ha^{-1} yr^{1}	Large increase in growth with increasing residue (39 months)
Australia (SW)	*E. globulus*	Mediterranean 1000 mm. 9 - 25 °C	Medium seasonal deficit	High	High >30 t ha^{-1} yr^{1}	Early growth differences disappear (48 months)
India (SW)	*E. grandis*	Tropical 3000 mm. 20 - 42 °C	No deficit	Medium	Medium 20 t ha^{-1} yr^{1}	No effect (12 months).
China	*E. urophylla*	Tropical 2200 mm. 15 - 28 °C	Medium seasonal deficit	Very low	Low < 10 t ha^{-1} yr^{1}	No effect (31 months)

Modified (Gonçalves *et al.,* 2004)

ADVANTAGES OF MULCHING

Mulching harvest residues offers advantages that are difficult to quantify in terms of long-term economic and sustainability benefits. However, broad estimations based on actual case studies (Figure 2.11) are presented:

1. Mulching aids in decreasing fire spread and intensity by breaking residue down to a more compacted form (Da Costa, 2008). Mulched areas, prepared 3 months prior assist in retarding a fire front, allowing fire crews a short window of respite in which to create fire lines. There are unpublished records from 2007 to support this in SE Mpumalanga, South Africa (Figure 2.11, Figure 2.12). During a particularly severe fire with a strong NW wind gusting at over 80 km/h (blue arrow - Figure 2.13), no fires entered the mulched area (green demarcated area - Figure 2.13) and a planted area (multiple age classes) of 450 ha was protected. The mulched flank was extinguished within 48 hours after the main fire, freeing up valuable firefighting resources to combat burns spreading on multiple fronts (Da Costa, 2008).

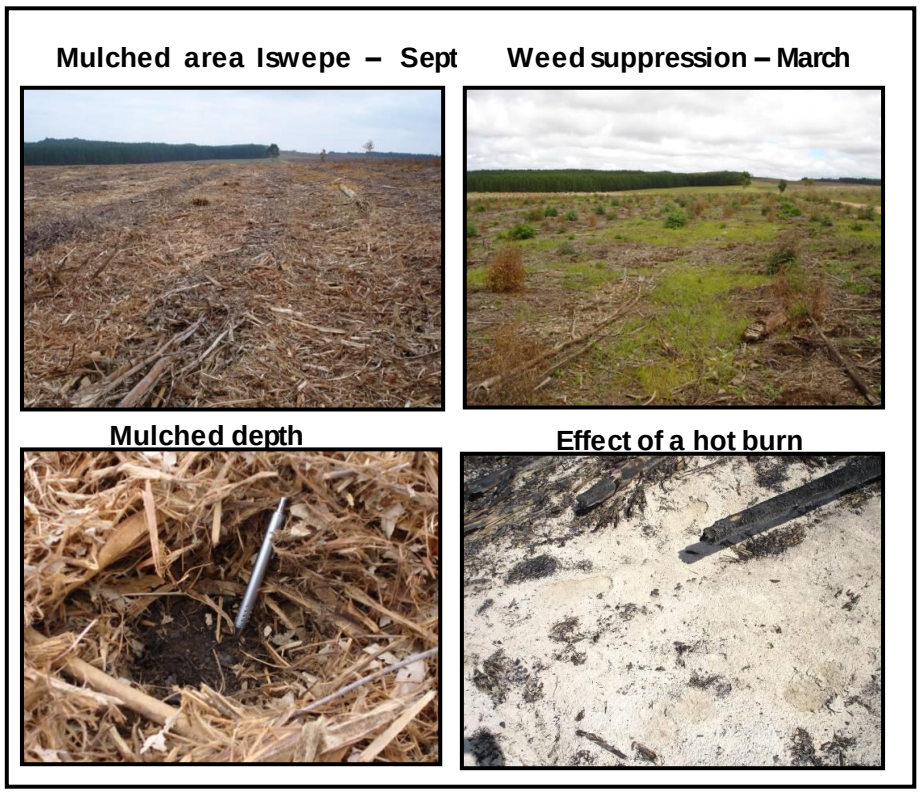

Figure 2.11: Mulching operations in Iswepe, SE Mpumalanga in contrast with a high intensity slash fire (hot burn) (Da Costa, 2008)

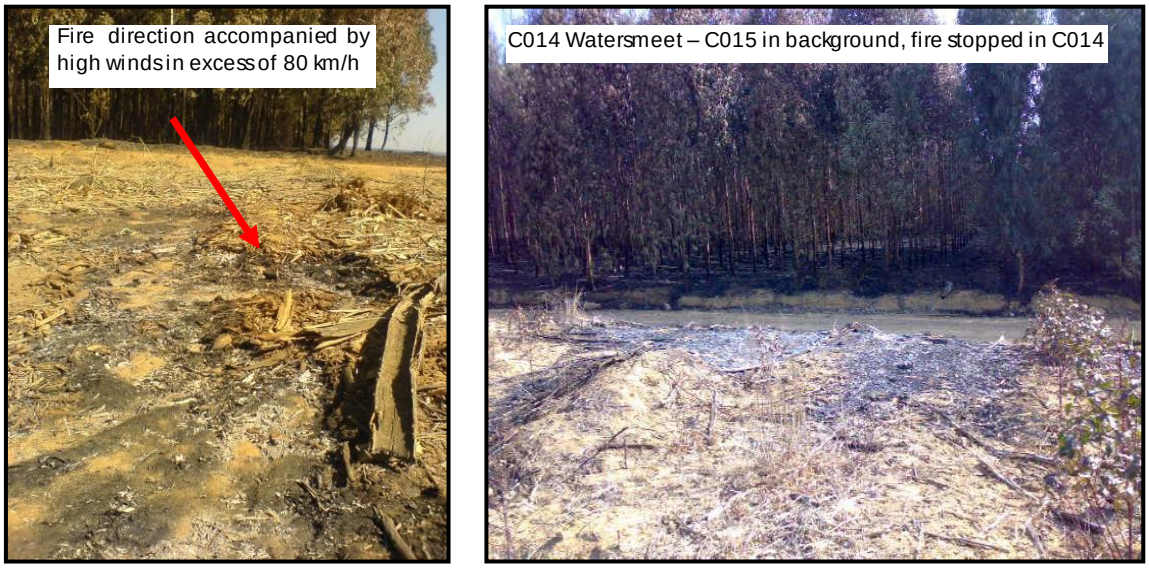

Figure 2.12: Retarding effect of mulch during a fire at Iswepe, SE Mpumalanga (Da Costa, 2008)

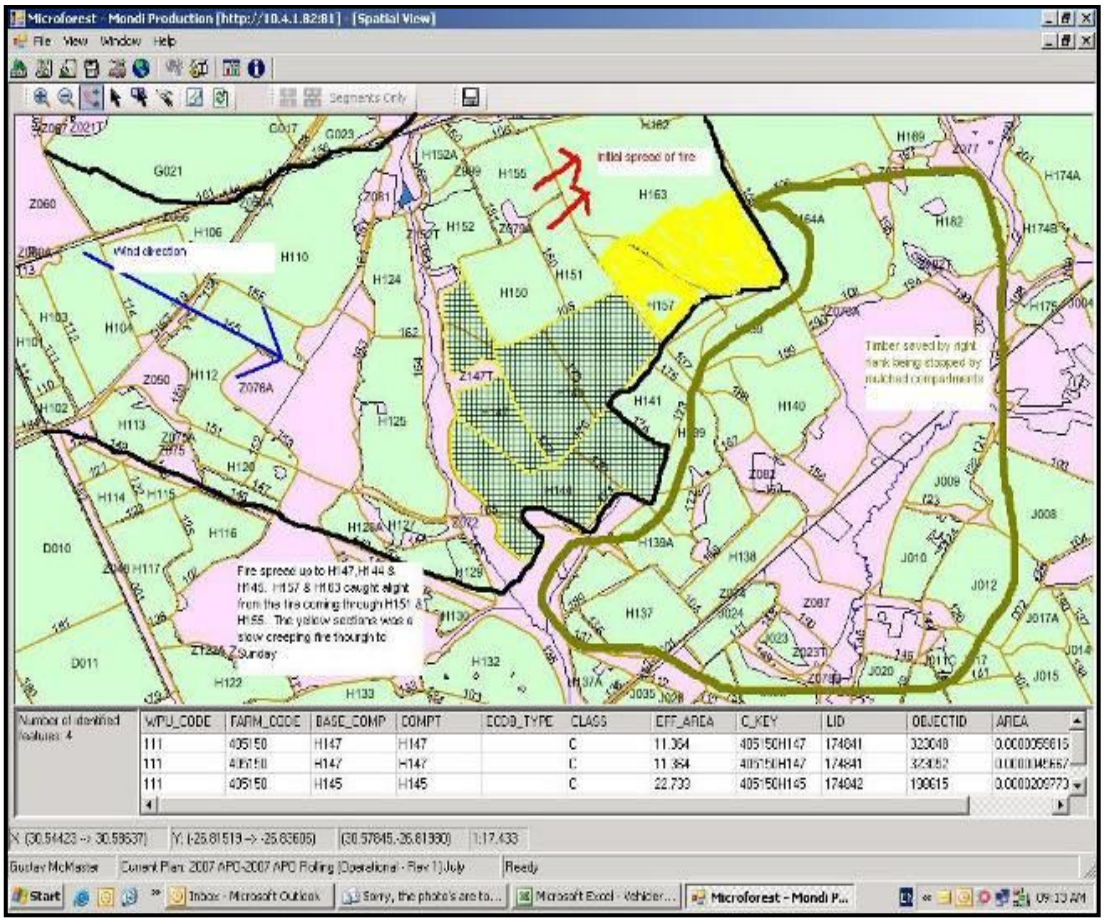

Figure 2.13: Map illustrating area saved at Iswepe through mulching (green outline) (Da Costa, 2008)

The value of standing timber protected, using company afforestation values and an average stand age of 4.5 years (Table 2.12), was calculated at approximately R10.5 million.

Table 2.12: Value of standing timber protected from fire through mulching

Benefit	Value/ha	Area	Total value
Salvage cost avoided	R 5,400	450 ha	R 2,430,000
Re-establishment cost avoided	R 4,500	450 ha	R 2,025,000
Standing timber saved (age class 4 years)	R 13,474.90	450 ha	R 6,063,705
Total saving	**R10,518,705**		

(Based on 2008 timber values. Average fire damaged stand age = 4.5 years) (Da Costa, 2008)

2. Compartment accessibility - The legacy of large multi-coppice stumps remains a concern and can be mitigated using a mulcher in a dedicated de-stumping role to improve access and create safer 'under-foot' conditions for workers, as well as expediting mechanisation of operations (Da Costa, 2008).

3. A mat of mulched residue (provided that it is not excessively thick) improves soil moisture retention leading to improved tree survival.

4. Mulching can inhibit weed seed germination and act as a physical barrier to weed growth (George and Brennan, 2002; Da Costa, 2008).

5. A reduction in prescribed burning of harvest residue on erosion prone soils. Efforts to reduce or eliminate burning on sensitive soils, especially on steep slopes are important. Decision support tools have been developed by forestry companies, based on lithology, soil form and slope to determine site suitability to prescribed burning. Although a cooler burn is desirable from an environmental perspective, the site can reignite with serious consequences under windy conditions. Mulching is therefore a viable, albeit expensive alternative (Da Costa, 2008).

Figure 2.14: Dry inter-row residue in *E. dunnii* coppice compartment, post first coppice reduction – Piet Retief Area, S.E. Mpumalanga

6. Mulching is effective as an inter-rotational tool and is not limited to clear-felled stands. One of the most vulnerable periods during a crop rotation is post first or second coppice reduction (Figure 2.14) when large volumes of combustible woody material are stacked on the inter-row and constitute a very high fire threat. Inter-row mulching of coppice-reduced stands have been trialled in Mpumalanga and shown to reduce fire vulnerability (Da Costa, 2008).
7. Timing of replanting – The utilisation of mulching, post harvesting operations, allows earlier replanting with limited delays waiting for suitable burning conditions. An additional 3 to 4 months of growing time can be added through earlier establishment on mulched sites Burning is wholly dependent on the first significant early summer rains (≥ 50.0 mm of rain over three consecutive days), the raising of the burning prohibition and suitable atmospheric conditions (wind speed, humidity and temperature). As productive timber areas decline, so the need increases to reduce temporary unplanted (TUP) areas to as low as possible. The introduction of mulching on a large scale (>1000 ha/annum) could aid in the reduction of TUP as land preparation can commence immediately once the threat of late frost have diminished (Da Costa, 2008).

DISADVANTAGES OF MULCHING

As experienced with all mechanized processes in forestry, the disadvantages include:

1. Machinery imported and purchase costs high with a purpose built 260 kW machine valued in excess of R 7.0 million.
2. Maintenance costs are expensive due to the extremely high wear on mulching heads.
3. The potential for a temporary N 'lock-up' must be considered. Although not well documented in this context, the carbon: nitrogen (C: N) ratio may be temporarily disrupted by the process of soil microbial immobilisation. The duration may be limited to a few months, strongly driven by prevailing weather conditions, and the degree of mixing of soil with milled organic residues. A rigorous fertilisation regime may be necessary to offset this impact.
4. Mulching does not kill multi-coppice eucalypt stumps. Unpublished results show that such stumps sprout vigorously once mulched (Da Costa, 2008).

2.17. WEED CONTROL AND RESIDUE MANAGEMENT INTERACTION

Gonçalves *et al.* (2004) state that timeous weed control interacts with residue management, fertilisation and thinning to encourage better tree growth. The impact of weeds on the availability of light to trees, specifically seedlings, is well documented; however, only in the last two decades has the importance of below ground competition been understood.

Nambiar and Sands (1993); Silva *et al*. (1997) report that weeds decrease nutrient availability to trees as the fine roots of both woody and herbaceous plants are concentrated in the upper soil horizon where nutrient availability, particularly N and P, is most available and root-length densities of weed species much higher than trees. Further competition for soil moisture can also be intense as indicated by leaf water potential studies (Nambiar and Sands, 1993). Silva *et al*. (1997) note that weed occurrence is much lower when residues are retained, thus obstructing the germination of the weed seed bank.

CHAPTER 3: MATERIALS AND METHODS

INTRODUCTION

Four trials were established at Mountain Home (KwaZulu-Natal Midlands) Estate, with two trials planted to *E. dunnii* seedlings and two planted to an *E. grandis x E. nitens* hybrid clone (Table 3.1). All trials were established from February 2011, (Area Office latitude: 29°34'05.58"S; longitude: 30°16'21.81"E) at compartments D010 (High productivity site: *E.dunnii*), E013 (Medium productivity site: *E. dunnii*), D01b (High productivity site: *E. grandis x E. nitens*) and F026 (Medium productivity site: *E. grandis x E. nitens*) (Figure 3.1 - Mondi GIS, 2014). Trial sites were determined by similarities in lithology (dolerite derived), soil form (all apedal type with humic A horizons), aspect (primarily hotter, westerly aspects) and very similar climatic variations, specifically mean annual precipitation (MAP) and mean annual temperature (MAT).

Figure 3.1: Distribution of trial sites across Mountain Home Estate, KZN also showing the position of main weather station used (Cedara) and an additional rainfall recording station in Hilton village

Table 3.1. Site characteristics for four *Eucalyptus* trials comparing re-establishment treatments for improved rotation-end performance

Region	Forest zone	KwaZulu-Natal - Midlands	KwaZulu-Natal - Midlands	KwaZulu-Natal – Midlands	KwaZulu-Natal - Midlands
	Magisterial district, Plantation	Hilton, Mountain Home	Hilton, Mountain Home	Hilton, Mountain Home	Hilton, Mountain Home
Trial Name		High productivity Compt D010	Medium productivity Compt E013	High productivity Compt. D01b	Medium prodcutivity Compt. F026
Latitude and Longitude		29°34´09.00˝S; 30°16´04.59˝E	29°33´31.54˝S; 30°17´08.17˝E	29°34´24.72˝S; 30°15´48.60˝E	29°31´45.53˝S; 30°17´44.24˝E
Altitude (m a.s.l.)		1 192	1 102	1184	1152
Aspect		W	W	W	N
Dominant slope (%)		0 - 15	0 - 15	0 – 15	0 - 15
Long-term mean annual rainfall (mm)		919	1047	919	1008
Long-term mean annual temperature (°C)		16.0	15.2	16.0	16.0
A-pan evaporation (mm)		1620	1620	1620	1620
Selected topsoil physical and chemical properties (0-15 cm)	Taxonomy (SA)[1]	Magwa (1100) – 85% Inanda (1100) – 15%	Kranskop (1100)	Magwa (1100) – 85% Inanda (1100) – 15%	Kranskop (1100)
	Formation[2]	Vryheid	Vryheid	Vryheid	Vryheid
	Taxonomy (FAO)[2]	Humic Ferralsol	Humic Ferralsol	Humic Ferralsol	Humic Ferralsol
	Depth (m)	0.50	1.50	0.50	1.2
	Texture	clay	Silty - clay	Sandy – clay loam	Sandy – clay loam
	Clay content (%)	28	27	35	35
	OC (WB)	2.4	1.9	2.5	2.2
	Weighted average PAW for trial site (mm)	36	47	108	81
	Total N (%)	0.40	0.40	0.34	0.25
	Bray #2 P (mg kg^{-1})	2.2	2.0	0.8	0.5
	Extractable K (%)	0.11	0.1	0.1	0.1
Spacing (stems per hectare - sph)		3.0 x 2.0 m (1667 spha)	3.0 x 2.0 m (1667 spha)	3.0 x 2.0 m (1667 spha)	3.0 x 2.0 m (1667 spha)
Species planted		*E. dunnii*	*E. dunnii*	*E. grandis* x *E. nitens*	*E. grandis* x *E. nitens*
Date planted		10 February 2011	4 March 2011	*10 February 2012*	*12 March 2012*
No. months @ final measure		99	98	87	84
Drought risk probability[3]	<850 mm	80 %	88 %	80 %	79 %
	<650 mm	3 %	1 %	3 %	2 %
Potential productivity[2]	Climate zone	CT8 (cool temperate)	CT9 (cool temperate)	ST8 (cool temperate)	CT9 (cool temperate)
	Growing conditions	Optimum	Optimum	Optimum	Optimum

MacVicar *et al*. (1988)[1]; MacVicar and De Villiers (1991)[1]; Fey (2010)[2]; Smith *et al*. (2005)[3]

3.1. TRIAL DESIGN

Each trial consisted of a 3 x 2 x 2 x 2 factorial arrangement of 24 treatments, replicated 4 times and arranged in a split-plot design. The main factors were slash management, plant size (root plug volume), hardening and insecticide, with slash management forming the whole plots, and plant size x hardening x insecticide forming the nested sub-plots (Table 3.2; Table 3.3). Each treatment plot consisted of 5 x 5 trees with the inner 3 x 3 trees measured. All trials were manually planted using a standard planting trowel at 3 x 2 m spacing (1667 stems ha^{-1}). Pits were prepared manually with a standard pick to a diameter of 30 cm and mean depth of 25 cm deep as per the establishment procedure. For the purpose of this document, cuttings and seedlings were referred to collectively as plants or nursery stock.

Table 3.2: Summary of field trials layout

Whole plot	Sub-plots		
Residue management	**Plug volume**	**Seedling quality**	**Insecticide**
Burn (B)	Large	Prime	Yes
Mulch (M)	Standard	Hardened	No
Spread (S)			

The four factors comprised:

1. Harvest residue management

a. **Spread:** Harvest residues retained. Residues were manually spread to a maximum of 20 cm thick layer as a manual operation using a standard garden rakes.

b. **Burned**: Treatments were burnt to a medium classification with the aim of only removing the H and L layers. The accuracy of such a level of burning precision is difficult to practically achieve but was generally within acceptable margins.

c. **Mulched**: Mulching was completed by the AHWI 200 mulching machine and was deemed acceptable after two passes per treatment. This reduced harvest residues to a broken down form.

2. Root plug volume (RPV) - Plant size (PS):

The two earliest trials were planted to genetically superior, second generation, orchard grade, *E. dunnii* seedlings and two latter trials to a commercially selected E*. grandis x E. nitens* hybrid clone (GxN108). Two different plant sizes were raised in black plastic Unigro® trays of the same geometry, double tapered with no air pruning slots, but differing volumes:

a. Standard: 128 cavity tray = 60 cm^3 $cavity^{-1}$.

b. Large: 72 cavity tray = 105 cm^3 $cavity^{-1}$.

The timing of the sowing of seed and placing of cuttings were synchronised according to

container size (standard size delayed), such that plants were of optimum morphological properties for that plug volume when planted. The larger plug were either sown or cuttings placed one month prior to the propagation of the standard plug treatment.

3. Hardening (H):

Drought conditioning of seedlings required reducing nursery irrigation to simulate dry field conditions bound to exist post-planting. Two irrigation-priming treatments were thus applied in the nursery, comprising:

a. **Primed plant (standard)** - Normal daily irrigation and fertigation regime applied to plant stock whilst in the nursery and 1.0 L of water applied at planting.
b. **Drought hardened plant (Hardened)** - 100% reduction of irrigation and fertigation up to 2 days per week (Thomas, 2009) applied for 4 weeks despatch, with 1.0 L of water applied at planting.

4. Insecticide (I):

A non-selective insecticide, Fastac SC L4992 (active ingredient: alpha cypermethrin), was applied at 0.5% concentration to control of white grub (*Scarabaeoidea* larvae) and cutworm (*Agrotis* spp.) (Atkinson and MacLennan, 1997) with no insecticide application applied to the control. All plots received 1 L of water whilst insecticide treatments received Fastac SC (alpha-cypermethrin) at 0.5% concentration. A follow up application of 350 ml (0.5% concentrate) Fastac SC solution was applied to insecticide treatments 10 days later. This is a standard operational practice as Fastac is sensitive to soil moisture. When soil is dry, cutworms tend to feed just below the surface and damage to seedlings is not visible until plants wither. When planting in dry soil, poor control of cutworm can be expected, as the pest is not exposed to product applied to the surface. Repeat application will not rectify the problem unless the soil is moist (BASF product catalogue, 2014). The two insecticide treatments were:

a. **Insecticide:** 1 ml alpha-cypermethrin (100 g a.i. L^{-1}) applied in 1 L water to each pit prior to planting. A follow up of 350 ml (0.5% concentrate) applied after 10 days.
b. **No insecticide**: 1 L water applied to each pit prior to planting.

Although trials were established within the planting window recommended for a cool temperate region (the period most favourable for initial plant survival and growth), the actual planting dates took place at the margins of the preferred planting periods to force a response when adverse planting conditions prevail.

Table 3.3: Summary of field trial design showing all plots and subplots (not randomised)

Whole_plots	Sub_plots	Residue_mgt	Plug_vol	Seedling_quality	Insecticide	Treat Codes
1	1	Burn (B)	Large (L)	Prime (P)	Yes (I)	B_L_P_I
1	2	Burn (B)	Large (L)	Prime (P)	No	B_L_P
1	3	Burn (B)	Large (L)	Hardened (H)	Yes (I)	B_L_H_I
1	4	Burn (B)	Large (L)	Hardened (H)	No	B_L_H
1	5	Burn (B)	Standard (S)	Prime (P)	Yes (I)	B_S_P_I
1	6	Burn (B)	Standard (S)	Prime (P)	No	B_S_P
1	7	Burn (B)	Standard (S)	Hardened (H)	Yes (I)	B_S_H_I
1	8	Burn (B)	Standard (S)	Hardened (H)	No	B_S_H
2	1	Mulch (M)	Large (L)	Prime (P)	Yes (I)	M_L_P_I
2	2	Mulch (M)	Large (L)	Prime (P)	No	M_L_P
2	3	Mulch (M)	Large (L)	Hardened (H)	Yes (I)	M_L_H_I
2	4	Mulch (M)	Large (L)	Hardened (H)	No	M_L_H
2	5	Mulch (M)	Standard (S)	Prime (P)	Yes (I)	M_S_P_I
2	6	Mulch (M)	Standard (S)	Prime (P)	No	M_S_P
2	7	Mulch (M)	Standard (S)	Hardened (H)	Yes (I)	M_S_H_I
2	8	Mulch (M)	Standard (S)	Hardened (H)	No	M_S_H
3	1	Spread (S)	Large (L)	Prime (P)	Yes (I)	S_L_P_I
3	2	Spread (S)	Large (L)	Prime (P)	No	S_L_P
3	3	Spread (S)	Large (L)	Hardened (H)	Yes (I)	S_L_H_I
3	4	Spread (S)	Large (L)	Hardened (H)	No	S_L_H
3	5	Spread (S)	Standard (S)	Prime (P)	Yes (I)	S_S_P_I
3	6	Spread (S)	Standard (S)	Prime (P)	No	S_S_P
3	7	Spread (S)	Standard (S)	Hardened (H)	Yes (I)	S_S_H_I
3	8	Spread (S)	Standard (S)	Hardened (H)	No	S_S_H

Work-study data for all residue management treatments are reflected for each trial (Table 3.4 and Figure 3.2). Replications per treatment were 1200 m^2 in area and a working day based on 480 minutes. The labour rate during the study was R 140.0 $unit^{-1}$. Preparatory data from compartment F017 was included in the study but the trial site abandoned due to fire damage that occurred prior to planting. Detailed productivity standards per replication are included (Appendix 1).

Table 3.4: Summary of costs and productivity pertaining to different residue treatments for trial series. Species reflected = previous crop

Compt	Species	Mulch R/ha (Actual)	Spread residue Unit/ha	Spread residue Rate/ha	Burn Rate Units/ha	Burn Rate/ha
E013	*E. grandis*	R 11 763.89	7.25	R 1 014.76	5.21	R 729.17
D010	*E. grandis*	R 13 826.39	4.38	R 612.50	12.07	R 1 689.24
D01b	*E.dunnii*	R 17 951.39	4.38	R 612.50	7.64	R 1 069.44
F026	*E.dunnii*	R 15 430.56	4.38	R 612.50	6.08	R 850.69
F017	*E.dunnii*	R 11 840.28	4.38	R 612.50	9.38	R 1 312.50
Trial mean		R 14 162.50	4.95	R 692.95	8.08	R 1 130.21

Note: Trial F017 prepared for planting but abandoned due to fire damage

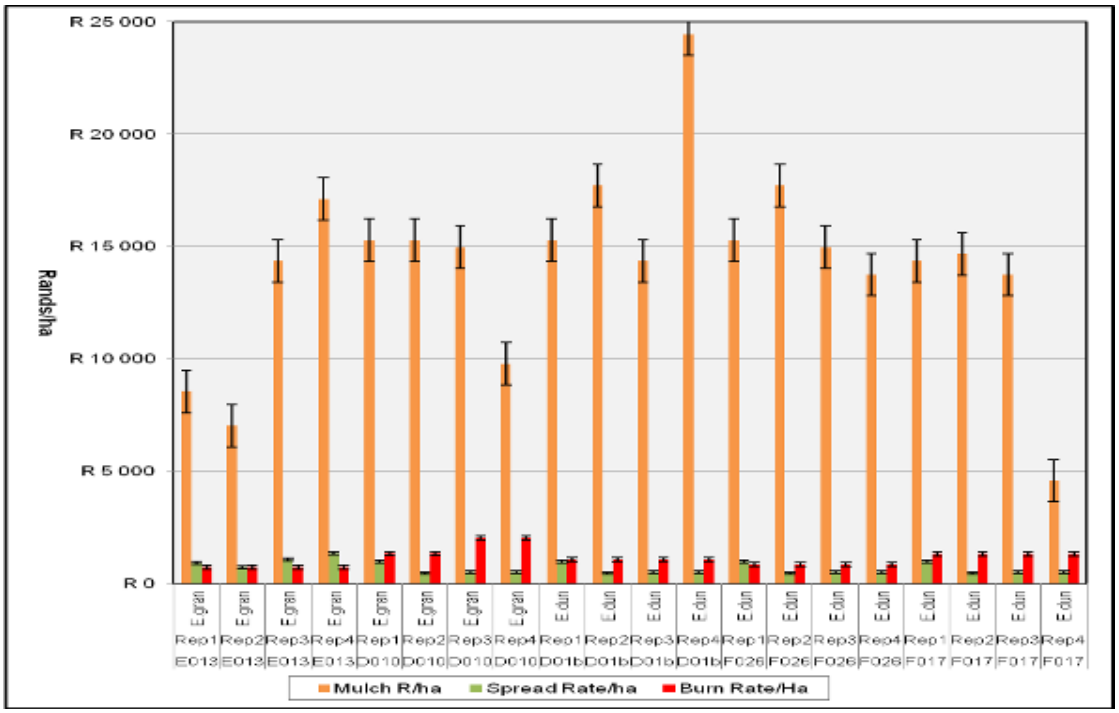

Figure 3.2: Cost data per replication and treatment for five trial sites. Error bar displayed using standard error

Mulch treatments were prepared using an AHWI RT200 tracked mulcher (Figure 3.4) due to the small size of individual treatments (1200 m^2) and the relative ease with which the mulcher can be transported. However, the RT200 (200 hp) is best suited to lighter mulch work (branch material), whereas the harvest residue for all sites could be classified as heavy (10 – 12 t ha^{-1}) and better matched to the more powerful RT400 model. Operational costs for the RT200 varied from R 7,500 ha^{-1} to R 9,000 ha^{-1} (1.5 hour ha^{-1} - 2.0 hours ha^{-1}), depending on branch diameter, presence of discarded coppice material (< 5.0 cm dia.) and diesel price fluctuations. A contributing factor to the higher trial mulching costs (mean = R 14,162.50) was the amount of additional turning due to treatment dimensions (1200 m^2). Not only did this hamper productivity but also affected mulch quality and hence the need for additional traversing of each site to achieve a more even mulch distribution. Actual mulching costs for each replication included fuel and driver costs but excluded transport between sites.

Manual spreading of harvest residue was very cost effective (mean = R 692.95); however, the task is not recommended due to safety and ergonomic concerns. The threat of dangerous underfoot conditions, the potential for injuries from broken timber and poor ergonomics of the task are unacceptable. A comparison of manual residue spreading with Brazilian mechanised equipment (Figure 3.3) emphasizes the preference of the latter (Figure 3.4). Gonçalves *et al*. (2008) mention the benefits of not burning but place very little

emphasis on the costs of developing implements able to break up and spread residue for strip cultivation to be effectively applied. Mechanised spreading of residues, other than mulching, has not evolved to this degree in South Africa, primarily due to a lack of suitable equipment, but also the presence of relic stumps and steep terrain that hinder machine access.

Figure 3.3: Mechanised residue spreading units in Brazilian operations

The costs of controlled burning was not as low as anticipated (mean = R 1,130.21); however, it remains an effective fuel load technique.

Trees were spaced 3.0 m x 2.0 m, a planting density of 1667 stems ha^{-1} (Spha). All pits were prepared manually with a standard pick to a diameter of 30 cm and mean depth of 25 cm deep as per the establishment procedure. No hydrogels or fertiliser applications were added at planting. Planting positions were first prepared in retained residue and mulch treatments by removal of harvest residues (1 m diameter), following which pits (25 cm diameter x 20 cm deep) were manually prepared using a mattock. A pre-plant spray was carried out using glyphosate (360 g a.i. L^{-1} isopropylamine salt applied at 3 L ha^{-1}) to ensure sites were free from competing vegetation. Where necessary, weeds were controlled at each site through a combination of manual (ring weeding) and chemical (glyphosate) spray in the remaining areas. The replanting of dead trees (blanking) was complete within one month after planting; however, blanks were not included in assessments.

Figure 3.4: A & B - Spreading harvest residue treatment. C & D - Burn treatment. E & F - AHWI RT200 mulcher and completed mulch treatment

3.2. TRIAL DESIGN SUMMARY

The field trial design is summarised as follows:

1. Split plot type design with four replications per trial. Two field trials per genotype planted across four different sites in KwaZulu-Natal, South Africa.
2. The genotypes, clonal *E. gxn* and *E.dunnii* seedlings were all commercially improved stock from the Mondi tree improvement programme.
3. Plot size were 25 trees, planted in a 5 x 5-tree pattern. To calculate mortality percentages, a minimum of 100 plants per treatment were required. The inner 3 x 3 trees of each plot measured with two border rows limiting any edge effect.
4. Three harvest residue treatments, burnt, spread and mulched allocated per replication.

5. Clonal and seedling nursery stock, were raised in two black plastic tray types with the same insert design, the Unigro® 128 (60 cm^3) and Unigro® 72 (103 cm^3) designs.
6. Ninety-six (96) plots planted per trial, i.e. 3 residue treatments x 2 plug volumes x 2 plant quality treatments x 2 biotic treatments x 4 replications (Table 3.3).

3.3. HIGH PRODUCTIVITY SITE: COMPARTMENT D010

Mulching treatments were prepared on 2 November 2010 with a mean mulching cost of R13,826 ha^{-1} for the trial. Skewed mulch costs per hectare (Figure 3.5) were due to excessive non-merchantable timber left on site and do not reflect operational costs. The total mass (t ha^{-1}) of branch and bark residue for the trial = 17.21 t ha^{-1}, with a high standard deviation of 10.49 t ha^{-1}. The previous crop was planted to *E. grandis* and the mean residue mass for the trial series was 24.66 t ha^{-1}. The correlation coefficient for the trial series (*r)* for combined branch and bark mass (t ha^{-1}) to mulching costs (R ha^{-1}) was high (r = 0.84) and relationship linear.

Four burn treatments were prepared on 18 January 2011. Burning commenced at 10H20 under clear and ideal conditions but was terminated at 12H00 after completion of only two replications as ambient temperature rose to 30°C, accompanied by a light NE wind. Due to adverse weather conditions, burning would only resume on 2 February 2011 after 30 mm of rain. Burning conditions on 2 February 2011 were more favourable with an ambient temperature of 22°C and a cool SW wind at 5 km hr^{-1}. Burning of the remaining two replications commenced at 17H00 and ended at 19H10. The burning of randomised blocks (Figure 3.6) was a slow process and required 12.1 units ha^{-1} at a cost of R1,689 ha^{-1}, as opposed to a commercial standard of 3.5 units ha^{-1} or R490.00 ha^{-1}. Spreading of harvest residue was complete on 11 January 2011 at 4.4 units ha^{-1} and a cost of R 612.50 ha^{-1}. This activity closely mirrored operational performance and productivity standards.

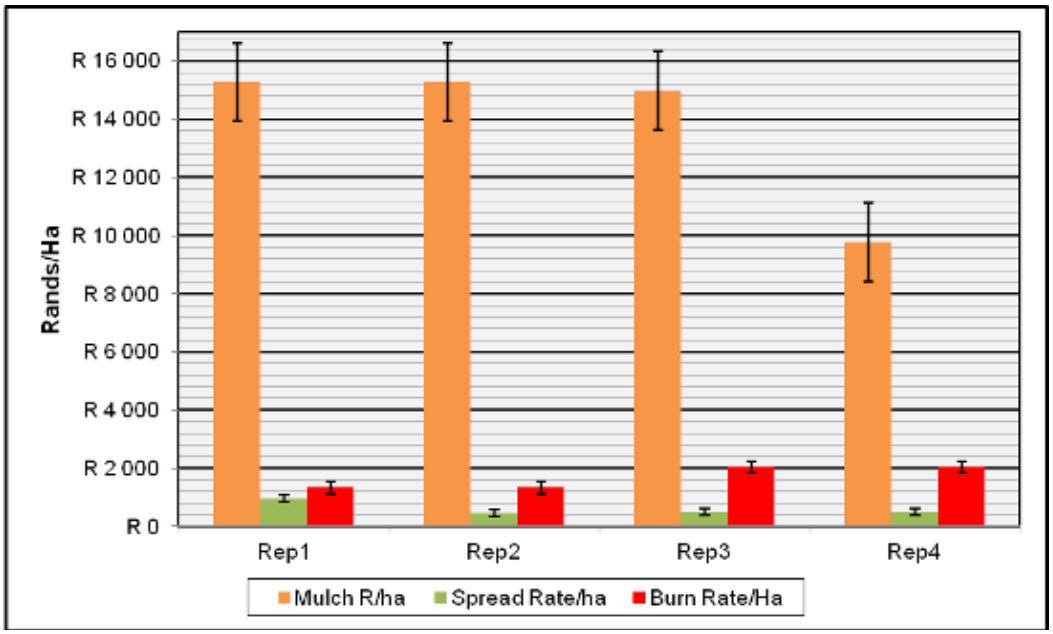

Figure 3.5: High productivity (D010) trial: Site residue productivity standards for treatments and replications. Error bar displayed using standard error

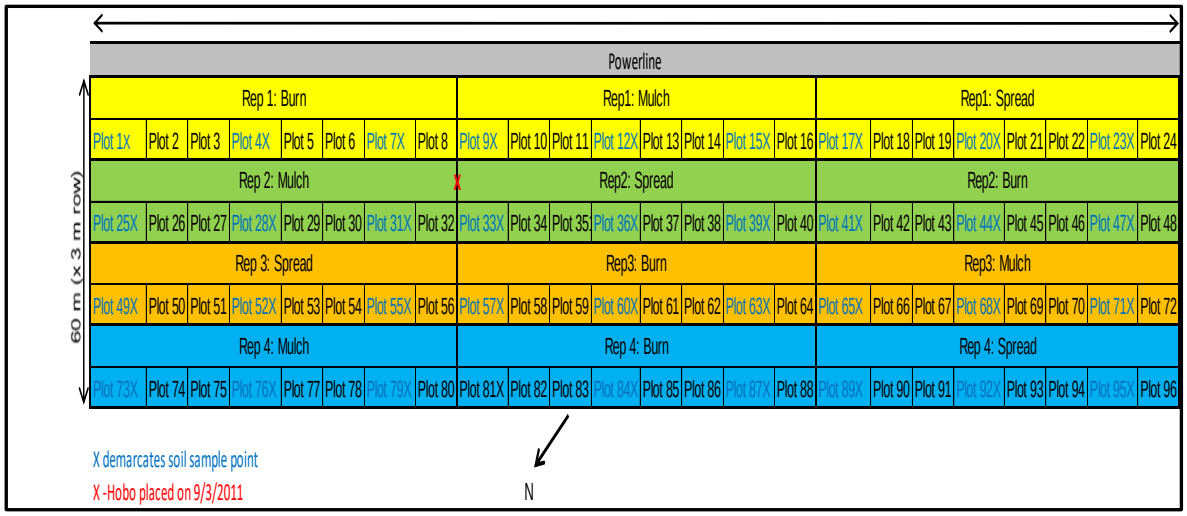

Figure 3.6: High productivity (D010) trial (D010) showing replications and plots

The high productivity site was pitted between 7 - 9 February 2011 and required 5.4 unit ha^{-1} to complete. Pits were 30 cm in diameter and 25 cm deep, measured at the centre point. Planting of second-generation *E. dunnii* seedlings commenced at 09H15 and finished at 16h35 on 10 February 2011. Weather conditions on the day of planting were warm with a maximum temperature of 25°C and a NW wind blowing at less than 5 km h^{-1} (Figure 3.7). Planting was preceded by 5 mm of rain the night before and a further 42 mm falling over the next ten days. All plots received 1 L of water, whilst insecticide treatments received Fastac SC (alpha-cypermethrin) at 0.5% concentration. A follow up application of 350 mm (0.5% concentrate) Fastac SC solution was applied to insecticide treatments 10 days later.

Thus, all plots treated with the insecticide application did receive an additional volume of water at 14 days.

Figure 3.7: Planting high productivity site (D010): A & B - *E. dunnii* seedling propagated in Unigro® 72 tray (105 cm³) and planted in burn treatment. C - *E. dunnii* seedling propagated in Unigro® 72 tray and planted in residue retained treatment. D – Planting operations in residue retained treatment. E & F - *E. dunnii* seedling, Unigro® 72 tray, planted in mulch treatment

3.4. MEDIUM PRODUCTIVITY SITE: COMPARTMENT E013

The medium productivity site was planted on 4 March 2011. Mulching treatments were prepared on 11 February 2011 at a mean mulching cost of R11,764 ha^{-1}.

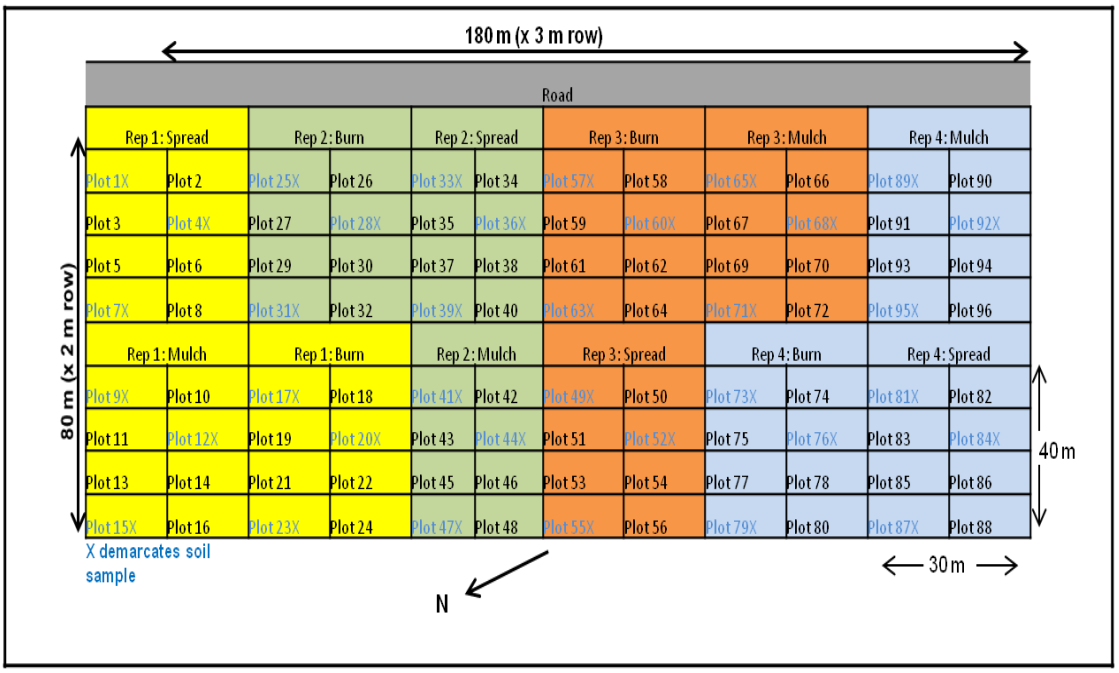

Figure 3.8: Medium productivity site map (E013) indicating replications and plots

The previous crop was planted to *E. grandis* with total mass of branch and bark residue equal to 14.2 t ha^{-1}, unevenly distributed across the site. The mean residue mass over five trial sites = 24.8 t ha^{-1}. Detailed productivity standards per replication are included (Appendix 1). The four burn treatments were prepared on 14 January 2011. Burning started at 13H50, under clear and ideal conditions, and was terminated at 16H00. Conditions were acceptable for a controlled burn with an ambient temperature of 27°C, accompanied by a light NE wind in the form of erratic gusts. The controlled burning produced a more satisfactory result than the trial at compartment D010. Burning required 5.2 units ha^{-1} at a cost of R 729 ha^{-1} as opposed to an operational standard of 3.5 units ha^{-1} and cost of R 490 ha^{-1}. Spreading of harvest residues was complete on 16 January 2011 using 7.3 units ha^{-1} at a cost of R 1,015 ha^{-1}. This was significantly higher than operational productivity standards (Figure 3.9).

The medium productivity site was pitted from 26 – 31 January 2011, utilising 5.0 units ha^{-1}, and pits prepared as per a company operational pitting procedure described for the previous trial. Planting of second-generation *E. dunnii* seedlings commenced at 08H30 on 4 March 2011 and was complete by 16h00. Weather conditions on the day of planting were hot with a maximum temperature of 32 °C and a NW wind gusting at 5 km h^{-1}. No significant rain

preceded planting and post-planting conditions were less than ideal, with only 19 mm of rainfall over the next 10 days. All plots received 1 L of water whilst insecticide treatments received Fastac SC at a 0.5% concentration, as previously described. A follow up application of 350 ml (0.5% concentrate) Fastac SC solution was applied to insecticide treatments 10 days later.

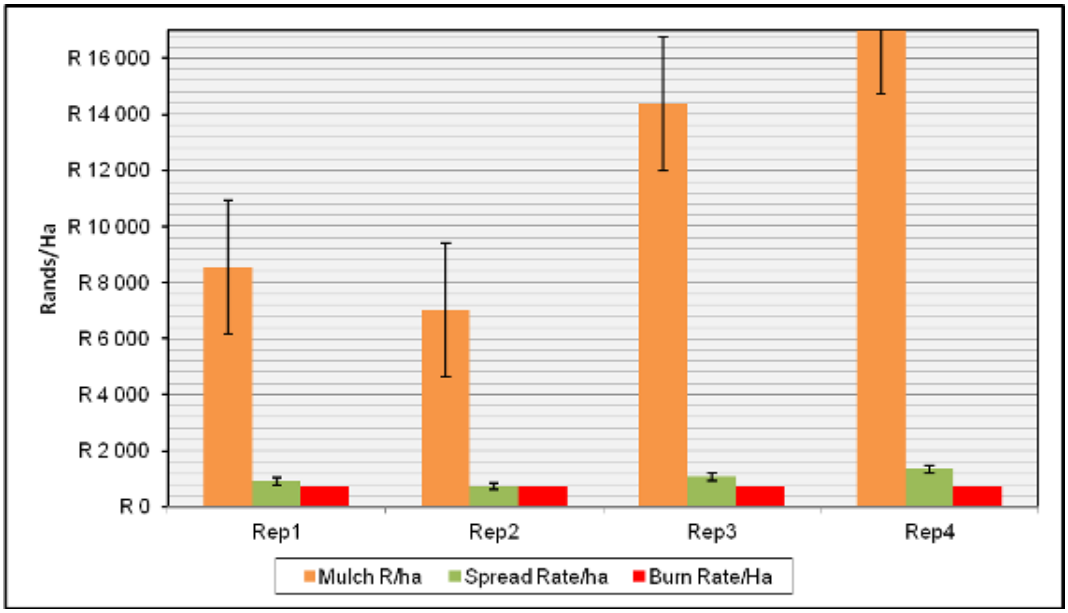

Figure 3.9: Medium productivity trial (E013): Residue productivity standards for treatments and replications. Error bar displayed using standard error

3.5. HIGH PRODUCTIVITY SITE: COMPARTMENT D01B

The medium productivity site *(E. gxn)* was planted on 10 February 2012 (Figure 3.10) with mulch treatments prepared three months earlier (2 November 2011) using the AHWI RT200 mulcher.

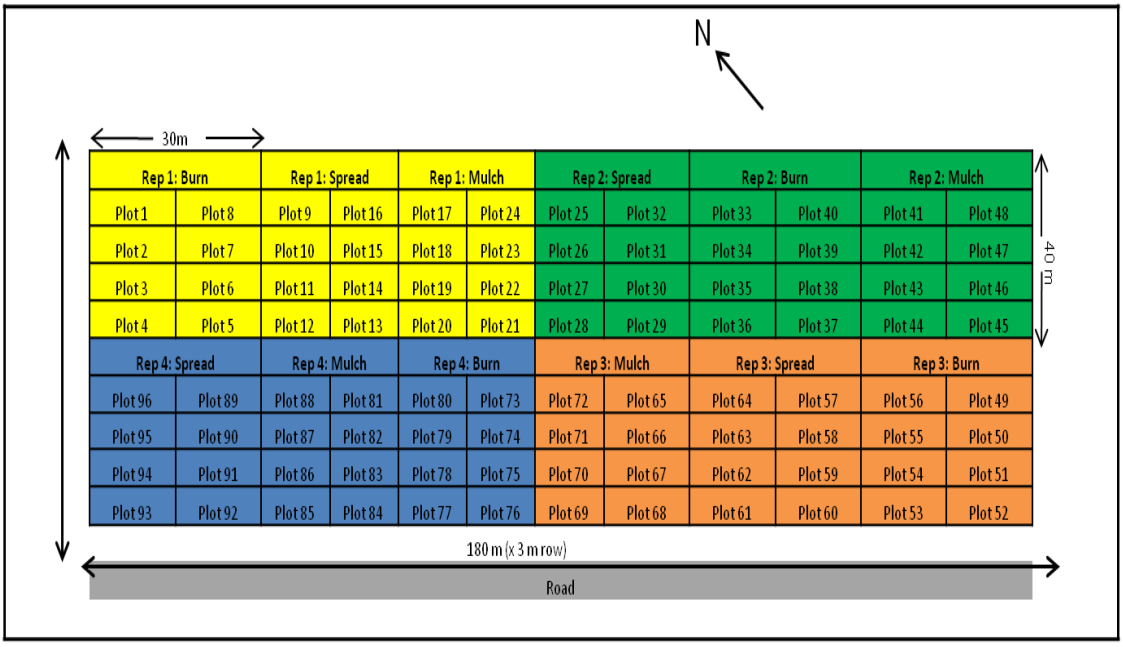

Figure 3.10: High productivity trial (*E. gxn* - D01b) showing replications and plots

The trial mean mulching costs of R 17,951 ha^{-1} were high due to an excess (Figure 3.11) of non-merchantable timber remaining on the site. The impact of species on mass (t ha^{-1}) of stem wood, bark and branches was significant for *E. dunnii* with total mass of branch and bark residue = 32.1 t ha^{-1} (SD = 10.5 t ha^{-1}) whilst the mean for the trial series = 24.7 t ha^{-1}. Combined branch and bark mass of *E. dunnii* was 114% higher (Figure 3.11) than *E. grandis* and the importance of the previous crop species must be factored into any calculation to determine an accurate mulching rate per hectare. Detailed productivity standards per replication are included (Appendix 1).

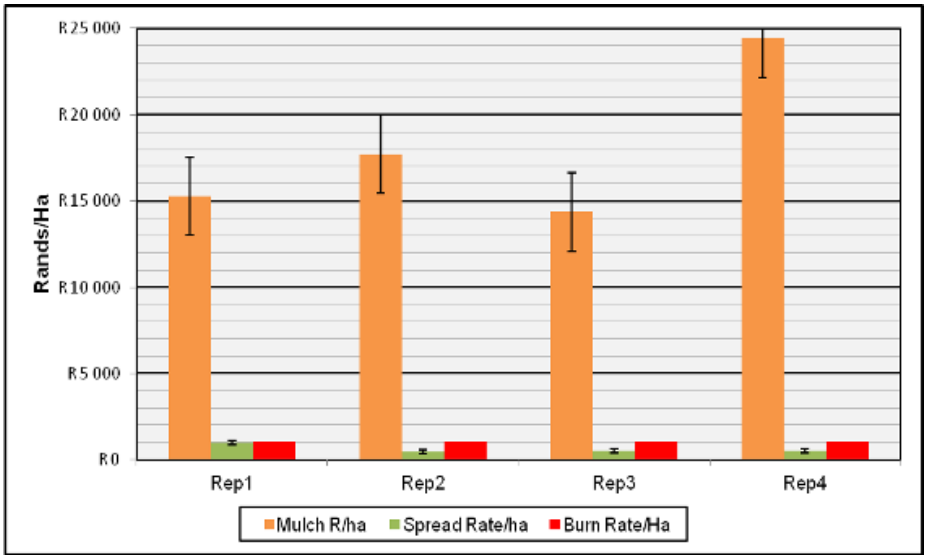

Figure 3.11: High productivity trial (*E. gxn* - D01b): residue productivity standards for all treatments and replications. Error bar displayed using standard error

The four burn treatments (Figure 3.12) were completed on 28 January 2012. Controlled burning started at 12H30 under clear and ideal conditions, and terminated at 16H00. Maximum temperature was 25°C accompanied by a light NE wind of 5 km hr^{-1}. Burning required 7.6 units ha^{-1} at a cost of R 1,069 ha^{-1} as opposed to an operational standard of 3.5 units ha^{-1} and cost of R 490 ha^{-1}. Higher burning costs were due to extra precautions applied during replication burns as the compartment lies on a westerly aspect with a slope of over 16%. Spreading of harvest residues was complete on 28 January 2012 at 4.4 labour units ha^{-1} and a cost of R 613 ha^{-1}. This was significantly lower than expected and did not correlate with the much higher (114%) *E. dunnii* branch and bark mass (t ha^{-1}) as opposed to compartments with *E. grandis* residue.

Pitting was undertaken from 2 - 3 February 2012 at 5.4 units ha^{-1} as per prescription. Planting of a commercial clone *E. grandis* x *E. nitens* clone took place from 08H00 to 16h00 on 10 February 2012 (Figure 3.12) and required 2.2 labour units ha^{-1}. Planting weather conditions were cool and wet with a maximum temperature of 23 °C, and 4.5 mm of rain falling on the day. Trial planting was followed by 49 mm of rainfall over 10 days. All plots received 1 L of water whilst insecticide treatments received Fastac SC at 0.5% concentration. A follow up application of 350 ml (0.5% concentrate) Fastac SC solution was applied to insecticide treatments 10 days later, as applied to preceding trials (Figure 3.12).

Figure 3.12: High productivity trial. A – *E. gxn* (hardened) clone - Unigro® 72 (105 cm³) plug planted in burnt treatment. B - Applying Fastac® insecticide to subplots in mulch treatment. C - *E. gxn* (primed) clone established in mulch treatment. D – Spread treatment

3.6. MEDIUM PRODUCTIVITY SITE: COMPARTMENT F026

The final trial was planted on 12 March 2012 (Figure 3.13). Mulching treatments were prepared on 3 November 2011 using the AHWI RT200 mulcher with mean mulching costs = R15,431 ha $^{-1}$. Mulching costs per hectare were governed by factors as described in the previous three trials.

Figure 3.13 Medium productivity trial (F026) showing replications and plots

The previous crop of *E. dunnii* played a significant role in the mass (t ha^{-1}) of residue remaining on the site. The total mass of branch and bark residue for Trial 4 equated to 35.1 t ha^{-1}, whilst the average for the five trials was 24.7 t ha^{-1} with a standard deviation of 10.5 t ha^{-1}. The extremely high residue mass was due to a greater final volume (m^3 ha^{-1}) than the high productivity trial at compartment D01b (233.9 m^3 ha^{-1} vs. R 214.0 m^3 ha^{-1} respectively). Interestingly, mulching costs (R 2 520.8 ha^{-1}) were lower than D01b. Based on trends from the previous four trials (one trial abandoned), it was anticipated that greater final volume would result in a higher component of non-merchantable timber and hence higher mulching costs (Figure 3.14); however, utilizable timber recovery from this trial was significantly better and hence the lower cost. Detailed productivity standards per replication are included (Appendix 1).

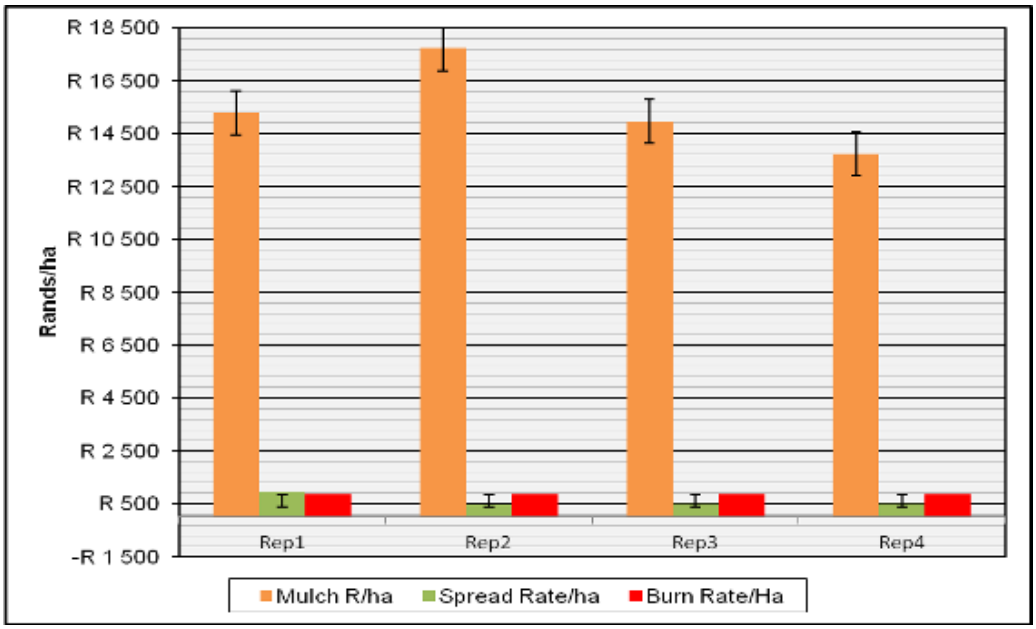

Figure 3.14: Medium productivity trial (F026): site residue productivity standards for all treatments and replications. Error bar displayed using standard error

Four burn treatments were prepared on 7 March 2012 (Figure 3.14). Burning started at 10H30 under ideal conditions and were complete by 16H00. Conditions becoming increasingly erratic for a controlled burn with an ambient temperature reaching 27°C, accompanied by a gusting NE wind, resulting in a hotter fire as compared to the high productivity site. The burning process required 6.1 labour units ha^{-1} at a cost of R 850.7 ha^{-1} compared to an operational standard of 3.5 labour unit ha^{-1} or R490.00 ha^{-1}. Higher burning costs were as a direct result of extra precautions required due to gusting winds that made burning rates unpredictable.

Spreading of harvest residue was completed by 6 February 2012 at 4.4 unit ha^{-1} at a cost of R 613 ha^{-1}. This was lower than expected and did not correlate with the *E. dunnii* residue mass (t ha^{-1}) calculated at 114% higher than the trials previously planted to *E. grandis*. The trial was manually pitted using road picks, 8 – 9 March 2012, at 6.0 unit ha^{-1}. Pitting costs were 11% higher than the previous trial as the soil was noticeably harder to prepare to an acceptable depth and tilth. Planting of the *E. gxn* clone (GxN108) was carried out between 08H00 and 16h00 on 04 April 2012 at 2.5 units ha^{-1}. Maximum temperature on the day of planting was 29 °C, accompanied by 15.0 mm of rain, followed by a further 29.0 mm over the next 10 days. All plots received 1 L of water, with insecticide treatments receiving Fastac SC at a 0.5% concentration. A follow up application of 350 ml (0.5% concentrate) Fastac SC solution was applied to insecticide treatments 10 days later as for preceding trials.

3.7. FIELD TRIAL MEASUREMENTS

Field measurements extended from day of planting (Day 0) through to rotation age, with final measurements for *E. dunnii* trials (Trials 1 & 2) terminated at 98 – 99 months and *E. gxn* trials (Trials 3 & 4) assessed at 84 – 87 months (Table 3.5). Critical assessments were at 12 months, 24 months, 36 months, 48 months and rotation age.

Table 3.5: Morphological and physiological measures for field trials

Measurement	Trial 1 (*E. dunnii*)	Trial 2 (*E. dunnii*)	Trial 3 (*E. gxn*)	Trial 4 (*E.gxn*)
Ht @ plant (m)	X	X	X	X
GLD @ plant (mm)	X	X	X	X
Ht @ 3 months (m)	X	X	X	
GLD @ 3 months(mm)	X	X	X	
Crown dia @ 3 months (m)	X	X	X	
Stomatal conductance @ 3 months (mmol $m^{-2}s^{-1}$)	X	X	X	
Chlorophyll content index @ 3 months (CCI)	X	X	X	
Ht @ 6 months (m)			X	X
GLD @ 6 months(mm)			X	X
Crown dia @ 6 months (m)			X	X
Stomatal conductance @ 6 months (mmol $m^{-2}s^{-1}$)			X	X
Chlorophyll content @ 6 months (CCI)			X	X
Ht @ 12 months (m)	X	X	X	X
DBH @ 12 months (cm)	X	X	X	X
Crown dia @ 12 months (m)	X	X	X	X
Stomatal conductance @ 12 months (mmol $m^{-2}s^{-1}$)	X	X	X	X
Chlorophyll content @ 12 months (CCI)	X	X	X	X
Ht @ 18 months (m)			X	X
DBH @ 18 months (cm)			X	X
Crown dia @ 18 months (m)			X	X
Stomatal conductance @ 18 months (mmol $m^{-2}s^{-1}$)			X	X
Chlorophyll content @ 18 months (CCI)			X	X
Ht @ 24 months (m)	X	X	X	X
DBH @ 24 months (cm)	X	X	X	X
Stomatal conductance @ 24 months (mmol $m^{-2}s^{-1}$)	X	X	X	X
Chlorophyll content @ 24 months (CCI)	X	X	X	X
Ht @ 36 months (m)	X	X	X	X

Measurement	Trial 1 (*E. dunnii*)	Trial 2 (*E. dunnii*)	Trial 3 (*E. gxn*)	Trial 4 (*E.gxn*)
DBH @ 36 months (cm)	X	X	X	X
Ht @ 48 months (m)	X	X	X	X
DBH @ 48 months (cm)	X	X	X	X
Ht @ 60 months (m)	X			
DBH @ 60 months (cm)	X			
Ht @ 84 - 87 months (m)			X	X
DBH @ 84 - 87 months (cm)			X	X
Ht @ 98 - 99 months (m)	X	X		
DBH @ 98 - 99 months (cm)	X	X		

Derived measures included corrected ground level diameter (GLD = GLD * % survival), biomass index (RCD^2 x Ht), and crown measurements. Crown diameter was calculated by measuring the widest and narrowest crown widths at right angles to one another and calculating the mean. Crown diameter (m) measurements ceased at 24 months as the canopy midpoint had become physically impractical to reach. Measurements across all sites were complete within a 10-day window to limit inaccuracies and for trial comparisons to be valid (Little, pers. comm., 2008).

3.8. PHYSIOLOGICAL MEASURES

Measures of physiological activity, including chlorophyll content index (CCI) and stomatal conductance (mmol $m^{-2}s^{-1}$) were recorded up to 24 months. Thereafter, canopy closure had occurred with cladaptosis (natural pruning) quite advanced and mature, fully expanded leaves senescent and generally unresponsive to meaningful readings.

Stomatal conductance and chlorophyll content index were initially measured at mid-day when water stress is assumed highest (Rolando and Little, 2005). However, fluctuating data necessitated revising the morning measurement to commencing at 08H00 and not exceeding one hour before excessive variation occurred. An Opti–Science Chlorophyll Content meter was used to measure chlorophyll content. Changes in chlorophyll content occur due to nutrient deficiencies, environmental stress and light intensity variation. Chlorophyll has several distinct absorbance properties that the meter can utilise to measure relative chlorophyll concentration. Strong absorbance bands are present in the blue and red but not the green or infrared bands, hence the green appearance of a leaf and measuring the amount of energy absorbed in the red band offers an estimate of chlorophyll concentration present in the tissue (Opti-Science, 2005).

Nutrient concentrations of transplants prior to planting focused on bulked leaf analysis of primary and secondary macro elements, namely nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulphur (S). Analysis of leaf, petiole, root and small branch tissue was completed at an accredited laboratory in Nelspruit, Mpumalanga. Plant nutrient content for differing treatments at establishment were calculated by determining the nutrient concentration of non-foliar (shoot and roots) and foliar components and multiplying by their respective laboratory dry masses. These values, less the **mean** transplant nutrient content, yielded actual nutrient uptake by young trees. Sampling was limited to foliar and non-foliar aerial portions due to the difficulty in fully extracting an intact root system (Du Toit, pers. comm., 2008).

3.9. GENERAL SITE AND CLIMATE DESCRIPTION

The climate of Hilton, Kwa-Zulu Natal Midlands, is classified as cool temperate with a mean annual temperature (MAT) of 16°C and an altitude of 1200 m.a.s.l. Mean minimum temperature is 2°C with a mean maximum temperature of 25°C and a mean annual (MAP) precipitation of 900 mm. A-Pan evaporation total is recorded as 1620 mm. (Mondi GIS, 2009). The forestry site classification, based on climate for the summer rainfall regions of South Africa, records the area as a cool temperate zone (CT9) (Louw and Smith, 2012) that experiences moderate frost events during winter and hence temperate eucalypt species such as *E. gxn* and *E. dunnii* are widely planted. The natural vegetation is Midlands Mistbelt Grassland found in KwaZulu-Natal and Eastern Cape Provinces of South Africa, scattered in a broad belt comprising several major patches within an altitudinal range of 760 - 1400 m (Mucina and Rutherford, 2006).

3.10. SOIL DESCRIPTION

Louw and Smith (2012), referencing Ellis (2000) and Fey (2010), describe the soils of KwaZulu-Natal Midlands as intensely weathered, highly leached, apedal, red and yellow in colour, low in base status and well-drained clayey soils, with an exceptional accumulation of humus. These soils have evolved in areas that are relatively cool with high rainfall, dominated by plateau topography and gentle to moderate relief. They possess a diagnostic humic A-horizon, usually quite thick, but can also be thinner for the soil form occurring at higher cooler elevations as in this trial series (Figure 3.15). Subsurface horizons are rich in sesquioxides with red (hematite) or yellow brown (goethite) colours dominating due to advanced weathering and free drainage if the humus content is high.

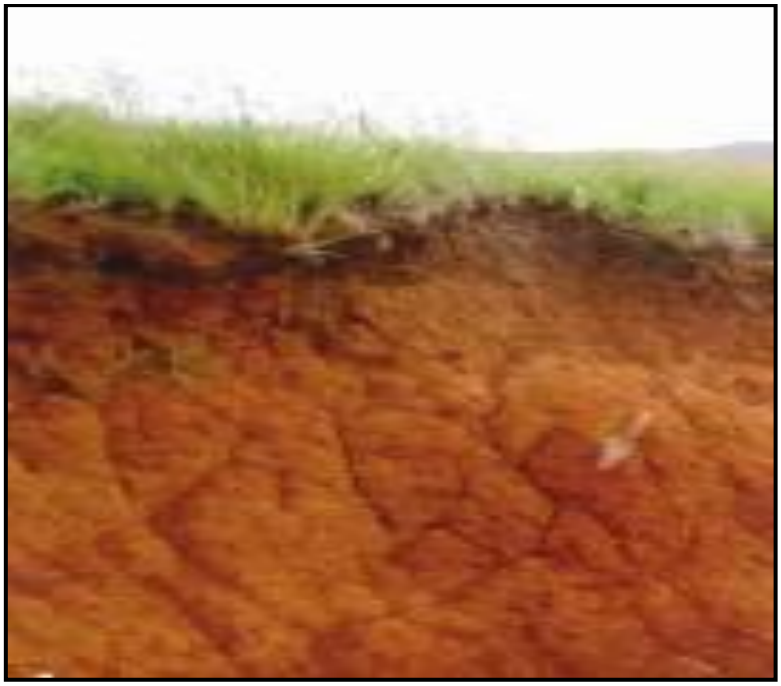

Figure 3.15: Humic soil group (Inanda form) that dominate the trial series (Photo M. Fey 2010)

The humic soil group generally show low cation exchange capacity (CEC) with a clay mineral composition dominated by kaolinite, aluminous chlorite, gibbsite and iron oxides. They are generally low in pH with a high phosphate fixing capacity and although possessing an inherently high biomass potential are limited by nutrient deficiencies, higher soil acidity, and the addition of fertilisers are essential to improve productivity in many plant crops. Aluminium toxicity is reported to form a complex within the humus layer making it less retentive towards nutrient cations (Fey, 2010). The soil forms of the reported trial series (Mountain Home Estate) have similar characteristics to those in the Karkloof area, approximately 20 km to the NW, and the site of an important study by Du Toit (2003).

Du Toit (2003) reports that the soils of the Karkloof trials formed under conditions of intensive weathering and leaching resulting in a strongly acidic soil with low effective CEC. The exchangeable complex is dominated by acid cations in the A and B1 horizons and exchangeable Ca, and K levels are low when compared to mean values of other shale derived forestry soils in South Africa (Table 3.6) (Du Toit, 2003). Exchangeable Mg levels in all soil layers are higher than that of Ca, and Na occupies a significant portion of the sum of base cations. The C: N ratio of 21 in the A-horizon is moderately high when compared to values of 10 - 13 recorded in tropical soils. Fey (2010) reports a C: N ratio = 10 in such soil forms, with a C percentage of 2%. A topsoil C: N ratio of 21 indicates modest rates of N mineralization and low levels of nitrification (Du Toit, 2003). The low extractable P (Bray-2) indicates that the quantity of readily available P is small; however, Du Toit (2003) notes that

highly weathered clays on the eastern seaboard of South Africa generally have high P-fixing capacities.

Table 3.6: Karkloof trial series - Soil properties prior to trial establishment

Depth (cm)	Bulk density g cm^{-3}	pH - KCl	pH - H_2O	C	N	C:N	P mg kg^{-1}	Exchangeable cations				Sum of bases	Extr. acidity	CEC
				(g kg^{-1})				Ca	Mg	K	Na			
								(cmol $_c$kg^{-1})						
0 - 20	0.9	3.94	4.33	66.5	3.2	21.3	2.75	0.43	0.64	0.16	0.23	1.46	3.25	4.71
20 - 40	1.21	4.23	4.87	42.3	1.8	23.7	0.94	0.33	0.56	0.11	0.21	1.20	1.48	2.68
40 - 60	1.35	4.40	5.13	23.5	1.2	20.4	0.34	0.31	0.55	0.09	0.21	1.16	0.81	1.97

(Modified - Du Toit, 2003)

Such soils are prevalent across the eastern escarpment of KwaZulu-Natal, Mpumalanga, Swaziland and Limpopo Provinces and well suited to commercial forestry. Common soil forms include Kranskop, Magwa, Inanda, Sweetwater, Hutton, Clovelly and Griffin and Louw and Smith (2012) state that their top soils are generally humic in nature, i.e. soils high in finely divided organic material. All four trials contained Kranskop 1100, Magwa 1100, and Inanda 1100 soil forms, and according to Fey (2010) classified as Ferralsols (IUSS Working Group WRB, 2006 classification). Fey (2010) notes that where native vegetation still predominates, Ferrasols retain soil moisture, with little desiccation of the subsoil, that is directly attributable to low temperatures during the dry season that coincide with winter. The mean annual temperature (MAT) for the four trials varied from 15.6 °C - 16.6 °.

Visible cracking and contraction occurs where exotic forest plantations with high water demands (*Pinus* and *Eucalyptus*) have been planted for extended periods and subsoils indicate marked shrinkage due to intense drying. Generally, this group of soils is resilient and can withstand a fair amount of physical and chemical exploitation without deteriorating markedly (Fey, 2010). According to Evans (1999), the planting of short rotation timber crops such as eucalypts affect soil conditions in three ways:

1. Site preparation and establishment may modify the micro-site by improving soil physical conditions such as drainage, aeration, and compaction.
2. Tree growth modifies local hydrology through rainfall interception, moisture uptake and permeability through root channel formation. It may affect soil erosion rates through suppression of ground vegetation and the build-up of a litter layer.
3. Poor harvesting practices frequently lead to localized soil erosion, compaction and damage to organic matter.

3.10.1. TRIAL SOIL MEASUREMENTS

Three samples of each treatment and replication were collected from A and B-horizon on 5 March 2011 (Figure 3.16). Each sample point was scraped to bare mineral earth prior to sampling. The first and second cored samples of 15 cm each were regarded as constituting the A-horizon. The second sample core of 15 cm, A-horizon, was submitted for analysis. The third and fourth cores were discarded as the transition between A and B-horizons, whilst the fifth sample of 15 cm soil core was deemed representative of the B-horizon. Three samples per treatment were collected for each of four replications (24 samples), at row 3 and tree no. 3 (Figure 3.16). Samples were analysed by the Soil Laboratory, Institute for Commercial Forestry Research (ICFR).

Soil concentrations of N, P, K, Ca and Mg and gravimetric soil moisture content for all harvest residue treatments were determined at time of trial establishment. Salau *et al*. (1992), Buerkert *et al*. (2000) state that these soil nutrients significantly increase under organic litter mulch as compared to unmulched sites and changes in soil nutrient status may affect tree growth. Soil temperature measurements across all trial sites were measured 15 cm below the soil surface (A-horizon) for a period of 24 months using four Decagon 5TE sensors downloading to a Decagon EM50 data logger with an accuracy level of within 4%(Decagon, 2009). The 15 cm depth ensured the sensor position remained in the middle of the A-horizon and a mean depth where most fine roots develop in the early stage of tree growth.

Figure 3.16: Soil sample collection from D010: 5 March 2011

3.11. TRIAL CLIMATE DATA

Long-term climate data from the ARC and Cedara Agriculture Research Station is described (Figure 3.17 – Figure 3.23).

3.12. HIGH PRODUCTIVITY SITE (D010): *E.DUNNII*

3.12.1. SITE DESCRIPTION

The high productivity site (Compartment D010) was located at latitude, 29°34'09.07"S and longitude, 30°16'04.59"E (centre point of trial) at an altitude of 1192 m. Dominant aspect (100% of trial) was westerly with a slope range from 0 - 15%. A high mean annual precipitation (MAP) of 919 mm with a mean daily minimum of 4°C and mean daily maximum of 25°C creates ideal timber growing conditions. Mean annual temperature (MAT) was recorded at 16°C and A-Pan evaporation calculated as 1620 mm (Mondi GIS, 2014).

Dominant soil form (Table 3.7) was classified as Magwa 1100 (89%), with an Inanda 1100 constituting 7% and Kranskop 1100, 4%. The Magwa soil form, derived from the Vryheid formation, had an effective rooting depth (ERD) of 10 – 50 cm and fine sand clay loam texture. Average A-horizon clay content for the trial site was 30% with an organic carbon (O.C.) content of 2.2%. Plant available water (PAW) of the Magwa soil form was 32 mm. The Inanda soil form, covering 7% of the East section revealed an ERD of 30 - 90 cm, a clay content in the A-horizon of 35% and organic carbon content = 2.4%. Plant available water (PAW) = 79 mm.

Table 3.7: High productivity site (D010) soil properties summary

Plot	Slash_mgt	RPV	Hardening	Insect	Aspect	Slope class (%)	Soil form	PAW	Clay (%) A horizon	OC (%)	A-horizon depth (cm)	B-horizon depth
1 to 17	Burn	Large	No	Yes	W	0 - 15	MA1100	32	25	2.3	10	50
18 to 24	Slash	Large	No	No	W	0 - 15	IA1100	79	35	2.5	30	90
25 to 70	Mulch	Large	No	Yes	W	0 - 15	MA1100	32	25	2.3	10	50
71 to 72	Mulch	Large	No	No	W	0 - 15	Kp1100	37	30	2.5	20	70
73 to 94	Mulch	Large	Hardened	No	W	0 - 15	MA1100	32	25	2.3	10	50
95 to 96	Slash	Standard	Hardened	No	W	0 - 15	Kp1100	37	30	2.5	30	90

3.12.2. CROP HISTORY – HIGH PRODUCTIVITY SITE (D010)

Compartment D010 (14.3 ha) was previously planted to *E. grandis*, stock number M820, at a spacing of 3.0 m x 2.0 m (1667 trees ha^{-1}). Planted in December 2003 the compartment

was clear-felled in February 2010 at 7.01 years. Mean DBH at clearfell = 15.2 cm, dominant height = 21.3 m and mean tree volume = 0.14 m^3 with a final stocking of 1133 trees ha^{-1}. Clear fell volume = 159 m^3 ha^{-1} with total compartment volume at 2,278 m^3. No major outbreaks of pests or diseases were recorded over the rotation and the site was felled prior to the outbreak of the major national *Leptocybe invasa* outbreak.

3.13. MEDIUM PRODUCTIVITY SITE (E013): *E.DUNNII*

3.13.1. SITE DESCRIPTION

The medium productivity site (compartment E013) was located at latitude (Table 3.8): 29°33'31.54"S and longitude: 30°17'08.17"E (centre point of trial) at an altitude of 1102 m. The dominant aspect was westerly (100 % of area), with the 0 – 15% slope class accounting for 53% of the trial and 16 – 20% slope class the remaining 48%. Mean annual precipitation (MAP) = 1047 mm, with a mean daily minimum = 4°C and mean daily maximum = 25°C. Mean annual temperature (MAT) was 16°C and A-Pan evaporation calculated as 1620 mm.

Table 3.8: Medium productivity site (E013) soil properties summary

Plot	Slash_mgt	RPV	Hardening	Insect	Aspect	Slope class (%)	Soil form	PAW	Clay (%) A horizon	OC (%)	A-horizon depth (cm)	B-horizon depth
1 to 20	Slash	Large	No	Yes	W	0 - 15	MA1100	32	25	1.9	10	50
21 to 24	Burn	Standard	No	Yes	W	0 - 15	IA1100	116	30	1.8	30	90
25 to 44	Burn	Large	Hardened	No	W	16 - 20	MA1100	32	25	1.9	10	50
45 to 48	Mulch	Large	No	Yes	W	0 - 15	IA1100	116	30	1.8	30	90
49 to 76	Slash	Standard	No	Yes	W	0 - 15	MA1100	32	25	1.9	10	50
77 to 80	Burn	Standard	Hardened	Yes	W	0 - 15	IA1100	116	30	1.8	30	90
81 to 96	Slash	Standard	No	Yes	W	16 - 20	MA1100	32	25	1.9	10	50

The dominant soil form (Table 3.8) was Magwa 1100 (82%) with an Inanda 1100 constituting 18%. All soil forms possessed a fine sandy clay loam texture. The Magwa soil form showed an effective rooting depth (ERD) of 10 - 50 cm with an A-horizon clay content = 25% and organic carbon (O.C.) content = 1.9%. PAW of the Magwa 1100 = 32 mm soil depth. The Inanda soil form, covering 18% of the East section of the trial had an ERD of 30 - 90 cm, an A horizon clay content = 30%, OC = 1.8% and PAW = 116 mm.

3.13.2. CROP HISTORY MEDIUM PRODUCTIVITY SITE (E013)

Compartment E013 (11.2 ha) was previously planted to *E. grandis*, stock number M847, at a spacing of 3.0 m x 2.0 m (1667 trees ha^{-1}) in November 2003 and clear-felled in November

2010 at 7.09 years. Mean DBH at clearfell = 16.9 cm, dominant height = 24.2 m and mean tree volume = 0.20 m^3. Final stocking was recorded at a low 650 trees ha^{-1} with a clear fell volume = 131 m^3 ha^{-1} and total compartment volume = 1,472 m^3. No major outbreaks of any pests or diseases were evident prior to the national outbreak of *Leptocybe invasa*.

3.14. HIGH PRODUCTIVITY SITE (D01B): *E. GXN*

3.14.1. SITE DESCRIPTION

The high productivity clonal site (D01B) was located at latitude: 29°34'24.72"S and longitude: 30°15'48.60"E (at an altitude of 1184 m. The dominant aspect was northerly with the slope class 0 - 15% accounting for 50% of the trial and 16 – 20% the remaining 50%. Mean annual precipitation (MAP) = 919 mm with a mean daily minimum = 4°C and mean daily maximum = 25°C. Mean annual temperature (MAT) = 16°C and A-Pan evaporation = 1620 mm. The dominant soil form for the high productivity site was Kranskop 1100 (100%) with a fine sandy clay loam texture, effective rooting depth = 30 - 90 cm, an A-horizon clay content = 35% and OC = 2.5%. Plant available water (PAW) = 108 mm.

3.14.2. CROP HISTORY FOR HIGH PRODUCTIVITY SITE (D01B)

The high productivity clonal site was previously planted to *E. dunnii*, stock number M997, at a spacing of 3.0 m x 2.0 m (1667 trees ha^{-1}). The compartment, planted in December 2002, was clear-felled in February 2010 at 8.2 years. Mean DBH at clearfell = 17.4 cm, dominant height = 24.3 m and mean tree volume = 0.19 m^3. Final stocking was 1123 trees ha^{-1} with a volume of 214 m^3 ha^{-1} and final compartment volume = 4,751 m^3. No major outbreaks of any pests or diseases are on record.

3.15. MEDIUM PRODUCTIVITY SITE (F026): *E.GXN*

3.15.1. SITE DESCRIPTION

The medium productivity trial site (F026) was located at latitude: 29°31'45.53"S and longitude: 30°17'44.24"E at an altitude of 1152 m. The dominant aspects were northerly (56%) and easterly (44%), all within a slope range from 0 - 15%. Mean annual precipitation (MAP) = 1008 mm, mean daily minimum = 5°C and mean daily maximum = 25°C, whilst MAT = 16°C and A-Pan evaporation = 1623 mm. The dominant soil forms (Table 3.9) were Kranskop 1100 (57%) and Inanda 1100 (43%), both with a fine sandy clay loam texture. Effective rooting depth for the Inanda 1100 varied from 30 - 90 cm with an A-horizon clay content = 35% and OC = 2.2%. Plant available water (PAW) = 95 mm. For the Kranskop

1100 soil form, ERD = 30 – 60 cm, the A-horizon clay content = 35%, OC = 2.2% and PAW = 71 mm.

Table 3.9: High productivity site (F026) soil properties summary

Plot	Slash_mgt	RPV	Hardening	Insect	Aspect	Slope class (%)	Soil form	PAW	Clay (%) A horizon	OC (%)	A-horizon depth (cm)	B-horizon depth
1	Mulch	Large	Hardened	No	E	0 - 15	IA1100	95	35	2.2	30	90
2 to 4	Mulch	Standard	No	Yes	N	0 - 15	KP1100	71	35	2.2	30	60
5 to 36	Mulch	Large	No	Yes	E	0 - 15	IA1100	95	35	2.2	30	90
37 to 39	Slash	Standard	Hardened	No	E	0 - 15	KP1100	71	35	2.2	30	60
40	Slash	Large	No	Yes	E	0 - 15	IA1100	95	35	2.2	30	90
41 to 64	Burn	Large	Hardened	No	N	0 - 15	KP1100	71	35	2.2	30	60
65 to 66	Mulch	Large	Hardened	No	E	0 - 15	IA1100	95	35	2.2	30	90
67 to 68	Mulch	Large	Hardened	Yes	N	0 - 15	KP1100	71	35	2.2	30	60
69 to 72	Mulch	Standard	Hardened	No	E	0 - 15	IA1100	95	35	2.2	30	90
73 to 96	Slash	Standard	No	Yes	N	0 - 15	KP1100	71	35	2.2	30	60

3.15.2. CROP HISTORY FOR MEDIUM SITE PRODUCTIVITY (F026)

Compartment F026 was previously planted to *E. dunnii* (stock number M740) at a spacing of 3.0 m x 2.0 m (1667 trees ha^{-1}). The compartment planted in December 1998 was clear-felled in December 2010 at 12.2 years. Mean DBH at clearfell = 17.4 cm with a dominant height = 24.3 m and a mean tree volume = 0.19 m^3. Final stocking was recorded at 1238 trees ha^{-1} with a volume = 234 m^3 ha^{-1} and final compartment volume = 1,567 m^3. No major outbreaks of any pests or diseases are recorded.

3.16. CLIMATIC CONDITIONS OF TRIAL SITES

The ARC and Cedara Agriculture Research Centre supplied weather data for trial sites from 2010 to 2018. Additional daily rainfall data collected over a 10 year period by a local forestry company in Hilton, KwaZulu-Natal was also utilised. Distances of field trials (in kilometres) from the Cedara Weather Station and Hilton site are reflected (Table 3.10).

Table 3.10: Distance from trials to weather data Cedara Agriculture Research Station and 7 Forest Lane, Hilton

Trial	Latitude (s)	Longitude (E)	Distance to Cedara Weather Station (km)	Distance to Data Collection Point (7 Forest Lane) (km)
Trial 1 – D010	29°34'09.00	30°16'04.59	2.41	3.91
Trial 2 – E013	29°33'31.54	30°17'08.17	2.31	1.83
Trial 3 – D01b	29°34'24.72	30°15'048.60	2.94	4.51
Trial 4 – F026	29°31'45.53	30°17'44.24	3.44	2.72

Cedara Agriculture Research Centre data was collated from an automated weather station and historic data records. The numbers of years of data collection are indicated (Table 3.11; Figure 3.17 – Figure 3.23).

Table 3.11: Long term climate data - Cedara Agriculture Research Station

Measure	Unit	Years	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Av. Daily Max Temp	°C	94	25.37	25.38	24.73	22.93	21	19.13	19.58	21.01	22.49	22.69	23.55	24.86
Av. Daily Min Temp	°C	94	14.86	14.86	13.69	10.64	6.71	3.66	3.67	5.91	8.77	10.84	12.42	13.86
Av. Daily Max. RH.	%	31	93.3	93.69	93.33	92.75	88.91	84.43	82.12	83.13	87.31	91.37	92.57	93.35
Av. Daily Min. RH.	%	31	51.65	49.83	47.15	39.48	32.95	29.23	28.74	30.24	36.87	44.07	47.51	49.17
Av. Daily 'A' Pan Evaporation	mm	48	5.11	4.94	4.37	3.6	3.16	2.88	3.12	4.08	4.63	4.6	4.79	5.27
Av. Daily Sunshine Hours	Hours	91	6.36	6.73	6.76	7.39	7.88	7.99	8.1	8.02	7.15	6.28	6.24	6.25
Av. Daily Wind Run	Km day^{-1}	48	89	84.04	80.76	79.15	77.35	78.4	82.3	111.42	94.94	105.08	99.18	97.45
Av. Total Rainfall	mm	94	135.32	120.55	109.72	51.1	26.91	15.1	16.37	24.95	47.3	84.42	111.68	129.6
Av. Solar Radiation	Wm^{-2}	51	18.26	19.16	20.12	20.6	21.18	21.11	21.35	21.49	20.7	19.39	18.46	18.5
Av. V.P.D	kPa	51	7.82	7.93	8.00	7.77	7.86	7.43	7.67	8.30	8.63	7.83	7.57	8.09
Av. Frost days	days	51	0.00	0.00	0.00	0.04	0.76	3.44	2.43	1.58	0.20	0.04	0.00	0.00

(Cedara Agriculture Research Centre, 2008 - modified)

As part of the subtropics, albeit at altitudes in excess of 1100 m, solar irradiance (Wm^{-2}) (Figure 3.17) and CO_2 (ppm) concentrations were non-limiting, with mean solar irradiance = 20.02 Wm^{-2} (n = 653) and highest values recorded during winter when cloud cover is significantly reduced. Average daily sunshine hours = 7.8 hours day^{-1} (May – September), whilst summer = 6.8 hours day^{-1} (October – April) with cloud cover not solely limited to tropical thunderstorms, but also influenced by localised maritime effects, approximately 82 km direct distance to the coast, characterised by heavy mist during summer.

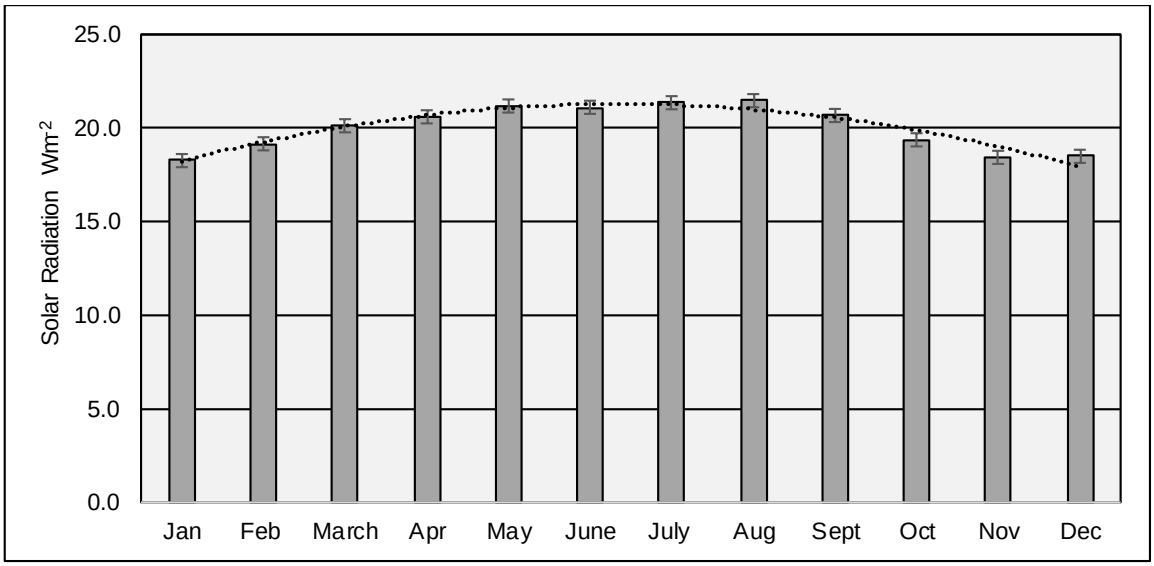

Figure 3.17: Mean monthly solar radiation - 51 years data. Error bar displayed using standard error (Cedara Agriculture Research Centre, 2008)

Weather patterns for the four trial sites followed the classical summer rainfall for eastern South Africa with maximum daily temperatures from November through to March (Table 3.11, Figure 3.18), followed by an autumn cooling period, commencing in April (Figure 3.18). Mean maximum temperature for Hilton = 22.6 °C (51 year records) with a mean minimum = 9.88 °C. Long-term mean monthly maximum and minimum temperature records are summarised (Table 3.18, Figure 3.18) and were accurate with trials 2 – 3 km from the Cedara weather station.

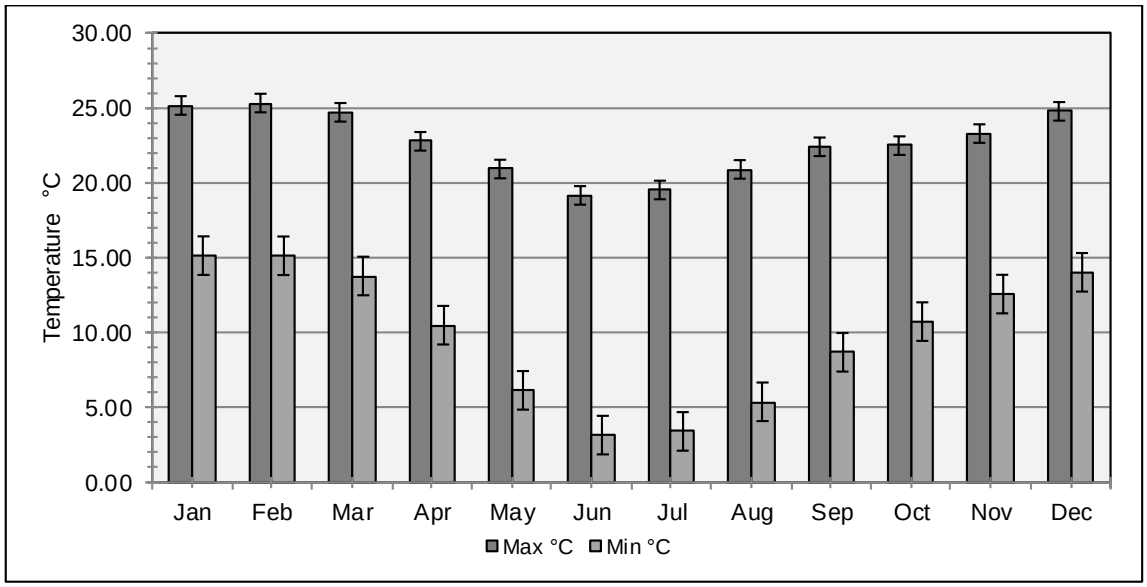

Figure 3.18: Mean temperature data for trial sites, 94-year data. Error bar displayed using standard error (Cedara Agriculture Research Centre, 2008)

Rainfall follows a summer pattern with September through to November typically quite dry (Figure 3.19; Figure 3.20; Figure 3.21) but with increasing diurnal temperatures and hence susceptible to increased moisture stress, expressed through an increasing vapour pressure deficit (VPD = kPa, Figure 3.22). The mean annual precipitation at Cedara weather station (measured over 94 years) = 873 mm. Nine years of rainfall data measured in Hilton (equidistant point to trial series) yielded an MAP of 1247 mm. The period, 2011 – 2013, was markedly wetter than average. Rainfall from 2016 – 2018 was markedly lower, driven by the *El Niño* Southern Oscillation (ENSO), with 2018 recording an MAP of 1003 mm (Figure 3.20). Historically, rainfall has fallen in every month of the year varying from 135 mm and higher in January to 15.0 mm in July. Winters have become increasingly drier over the last 3 years with some months recording no rain. Frost events for the KZN Midlands are prevalent between June and early August frost days ranging from 0 – 14 (51 years of records). No frost was recorded during the first year after establishment as all trials were positioned on warmer westerly aspects with gentle slopes (>10% slope) allowing for air movement towards valley bottoms.

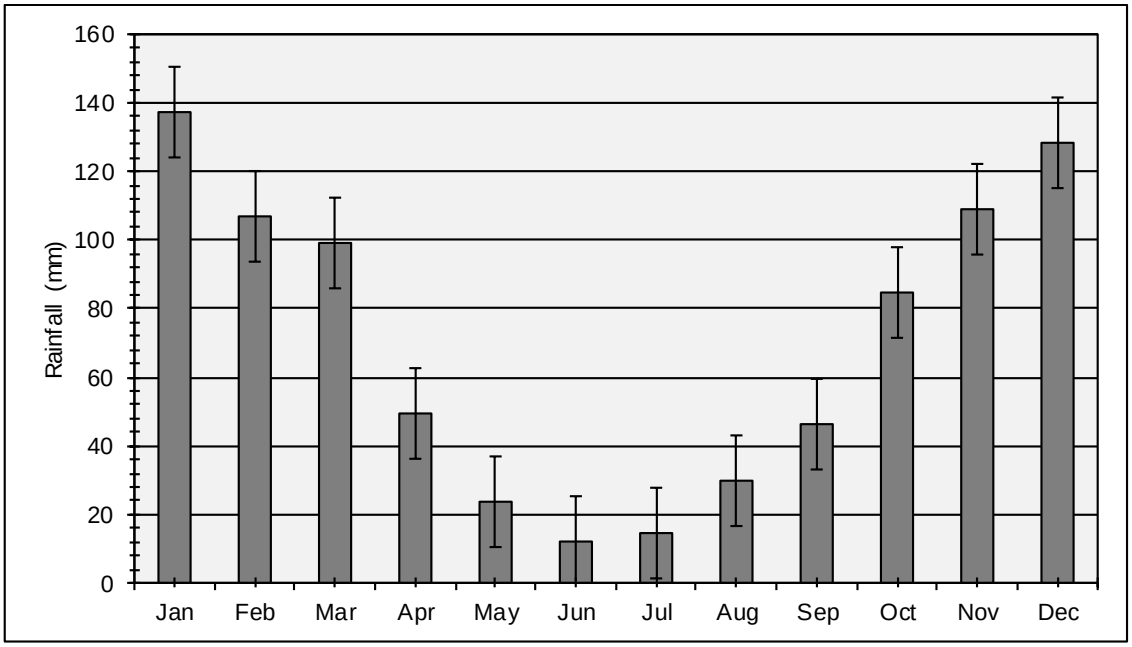

Figure 3.19: Mean monthly rainfall for trial sites, 94-year data. Error bar displayed using standard error (Cedara Agriculture Research Centre, 2008)

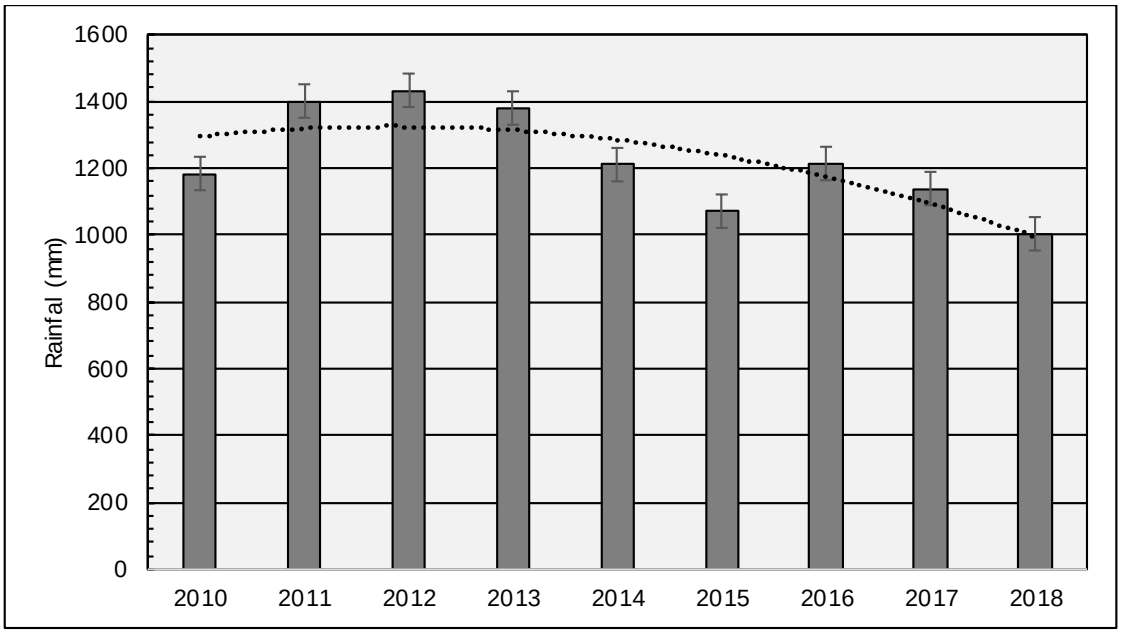

Figure 3.20: Annual rainfall for Hilton measured 2010 - 2018. Last 5 years showing MAP decline related to ENSO (Data – A. Bold, Mondi SA, Hilton)

Rainfall data from Cedara Agriculture Research Station and measurements recorded by A. Bold (Mondi, Hilton) showed good month by month matches from 2010 to 2017 (Figure 3.21) although the September to February period were much wetter in Hilton, most likely driven by an orographic effect.

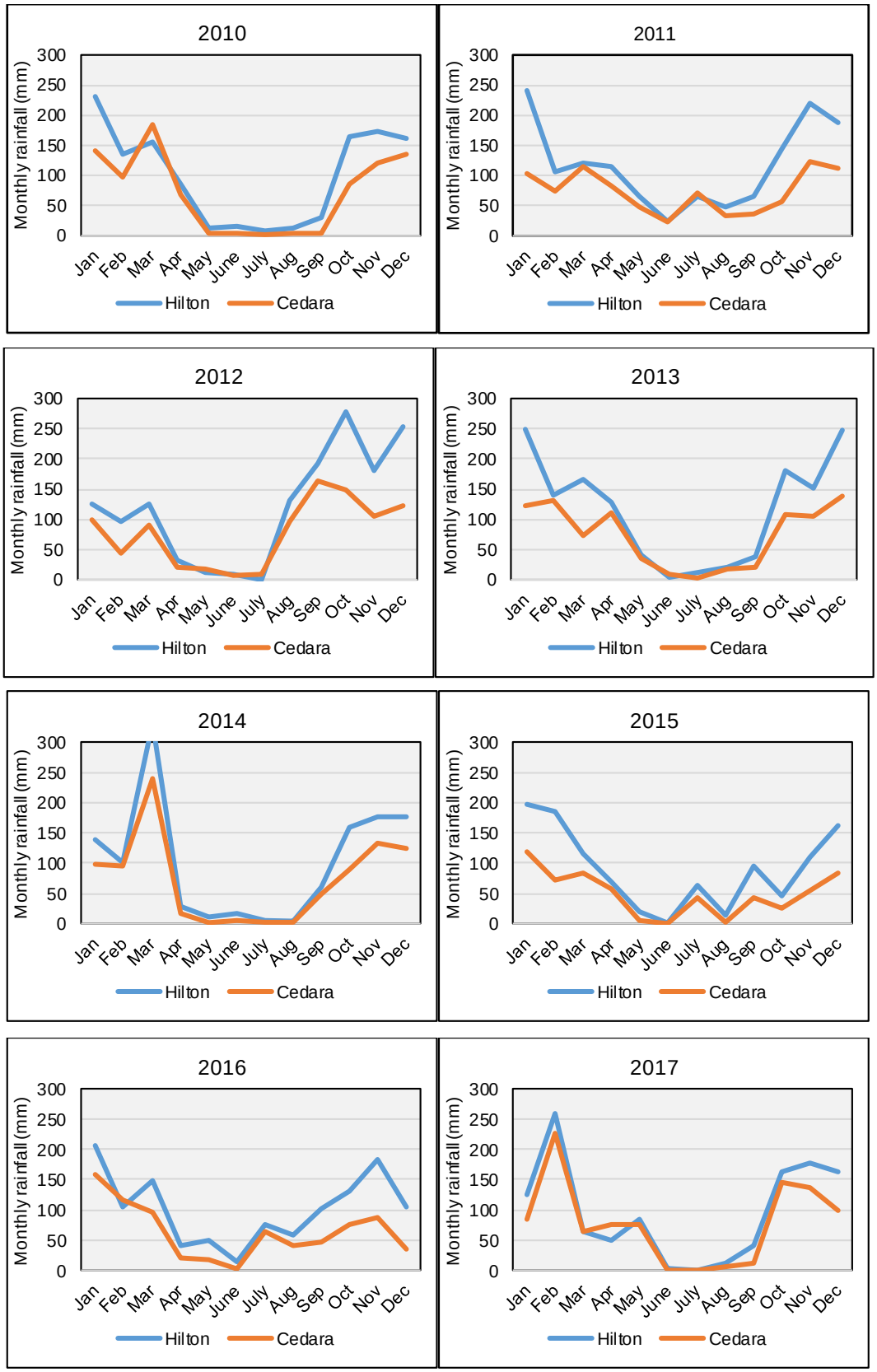

Figure 3.21: Monthly rainfall plotted for 2010 – 2017. Hilton rainfall consistently higher than Cedara from September – February due to an orographic effect (Hilton rainfall data, A Bold, 2018, Mondi SA, Hilton; Cedara – ARC. 2019)

The area experiences high relative humidity (RH %) levels with a mean daily range of 29 - 94 % (Figure 3.22) and variation largely driven by proximity to the ocean.

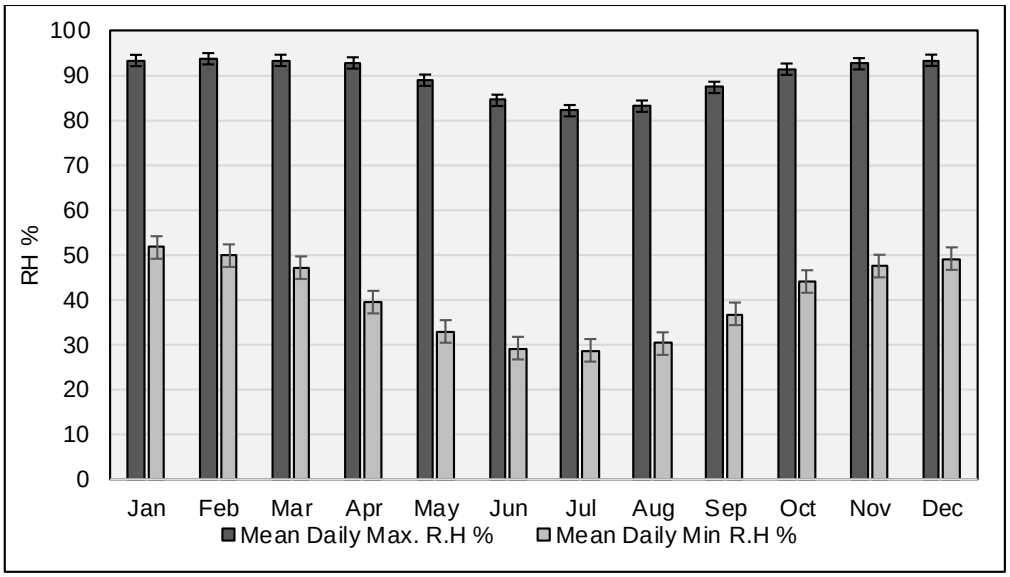

Figure 3.22: Mean daily max. & mean daily min. RH %, 31-year data. Error bar displayed using standard error (Cedara Agriculture Research Centre, 2008)

The benign nature of the climate, as expressed by moderate diurnal temperatures and relatively high humidity levels, produced vapour deficits (VPD) ranging from 0.5 – 1.2 kPa with a mean of 0.79 kPa (Figure 3.23). Such VPD readings, accompanied by soils with high clay contents, and consequently good moisture holding capacity, provide generally low levels of physiological stress; however, declining rainfall over the last 5 years has seen an increased VPD readings not reflected in the long term mean (Figure 3.23).

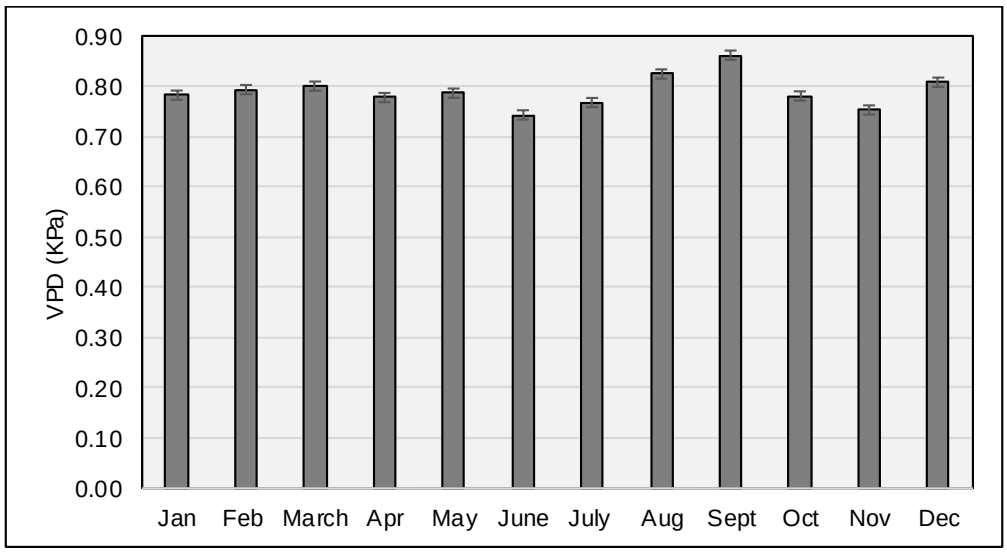

Figure 3.23: VPD (kPa) - Cedara Agriculture Research Station, 51-year data. Error bar displayed using standard error (Cedara Agriculture Research Centre, 2008)

3.17. POTENTIAL EVAPORATION AND WATER BUDGET FOR THE TRIAL SERIES

Palmer and Havens (1958) report that measuring transpiration and evaporation losses has always proven difficult and thus led to the development of formulae designed to estimate water loss directly from meteorological data. The conundrum has always hinged on the complexity of estimating soil moisture loss directly from meteorological data, albeit directly from bare exposed soil, or more complex, from vegetation in the form of evapotranspiration.

Palmer and Havens (1958) state that most empirical models fall into three groups:

1. Those involving the flux of water vapour.
2. Models utilizing the heat balance of the evaporating or transpiring surface.
3. Models that use an empirically determined relationship between evapotranspiration and one or more meteorological factors.

None of the above methodologies provides a complete solution to the problem of evaporimetry as all are based on some form of assumption, derived constants and technical complexities pertaining to measurements. Van Hylckama (1959), Cruff and Thompson (1967) report that climatological data developed by Thornthwaite in 1948 determined water budgets for natural watersheds and from controlled experiments for the humid north-eastern United States. Thornthwaite determined an empirical relationship between mean monthly temperatures, latitude of the location and E_p. Palmer and Havens (1958) add that the Thornthwaite method evolved from rainfall and runoff data for several drainage basins, determining an empirical relationship between E_p and mean air temperature. In spite of the inherent simplicity and limitations of this dated method, it remains sound, although not the most accurate.

Amongst the more obvious shortcomings of Thornthwaite's empirical relationship is the assumption of a high correlation between mean temperature and radiation, as well as atmospheric moisture and wind (Palmer and Havens, 1958). Thornthwaite and Mather (1958) record that whilst such factors may be unimportant under certain circumstances, there are occasions where solar radiation and atmospheric turbulence are the dominant factors in natural evaporation and Thornthwaite's empirical formula is applicable for any location for which daily maximum and minimum temperatures are available. In a study of six empirical models by Cruff and Thompson (1967) to compare potential evapotranspiration in arid regions of the United States, the Thornthwaite, U.S. Weather Bureau (a modification of the Penman method), Lowry-Johnson, Blaney-Criddle, Lane and Harnon methods were evaluated. Findings revealed the Blaney-Criddle method using

climatological data as the most practical for estimating potential evapotranspiration; however, not all the climate data necessary for this method was always available and hence the selection of the Thornthwaite model.

3.17.1. CALCULATING POTENTIAL EVAPORATION USING THORNTHWAITE

1. Potential evaporation

Thornthwaite model was applied as the simplest method to derive potential evapotranspiration (E_p). Thornthwaite (1948) showed a strong mathematical relationship between E_p and air temperature. The latitude of each trial area must be determined to calculate E_p. Heat index (I) is derived from a table compiled by Thornwaite (1948) that provides monthly heat index values with corresponding mean monthly temperature. The summation of monthly values for one year provides the required heat index and is represented by the equation (Pereira *et al.,* 2007):

$$Ep = 16(10T_n/I)^a \text{ Or } E_p = 1.6b\ (10t/I)^a \text{cm. (1)}$$

i. Where E_p = adjusted potential evapotranspiration (E_p) in cm or millimetres (mm = mean) for a 30 day period (mm month^{-1}).
ii. T = average monthly temperature in °C.
iii. I = yearly heat index. Equal to the sum of the 12-month heat indexes of i and i = $((t/5)^{1.514})$.
iv. *a* = cubic function of $I = (6.75 \times 10^{-7}) - (7.71 \times 10^{-5} I^2) + (1.792 \times 10^{-2} I) + 4.9239 \times 10^{-1}$ **.
v. b = correction factor for the unadjusted E_p values derived from Thornthwaite (1948) for different months (Pereira *et al.,* 2007).

2. Heat index

Ward (1967) states that the first step in developing a water budget is the determination of mean monthly temperature (°C), followed by a heat index (i).
The heat index can be calculated from the formula:

$$I = \sum_{n=1}^{12} (0.2\ T_n)^{1.514} \text{ (2)}$$

Where:

I = heat index.
T_n = Mean monthly air temperature (°C).

Alternatively: To determine E_p, calculate the heat index (I), or the sum of (i), from the formula:

***i* = ((t/5)1.514)** or values from a Heat Index Table (Pereira *et al.,* 2007; Thornthwaite, 1948).

3. Cubic function

A polynomial function is used to calculate the exponent ***a*.**

$$a = 6.675x10^{-7}I^3 - 7.71x10^{-5}I^2 + 1.7912x10^{-2}I + 0.49239 \quad ** \textbf{(3)}$$

Where:

a = Cubic function of ***a***

I = Heat Index

4. Solar Azimuth & Time of sunrise

The solar azimuth (δ) refers to the projected angle of the sun relative to its position in the plane of the local horizon. The Thornthwaite (1948) method requires the daily solar azimuth for each month of the year to determine the average monthly photoperiod. The first step requires calculating the daily solar azimuth angle for each site and the day-number of the year as an input variable **(4).** The second step determines the angle at time of sunrise **(h_n) (5).** This function incorporates the **solar azimuth value**, determined in the preceding step, and latitude of the region (Pereira *et al.,* 2007).

$$\delta = 23.45 * \sin\left[RADIANS\left(\frac{360(NDA-80)}{365}\right)\right] \quad \textbf{(4)}$$

Where:

δ = Solar azimuth (degrees)

NDA = Day number of the year

$$h_n = arcos[-tan\Phi * \tan\delta] \quad \textbf{(5)}$$

Where:

h_n = Angle at time of sunrise (degrees)

Φ = Latitude (degrees)

δ = Solar azimuth (degrees)

5. Average photoperiod

Photoperiod is defined as the time between sunrise and sunset for a given day or the duration of the day. To calculate the photoperiod, the angle at time of sunrise is required (6) (Pereira *et al.,* 2007).

$$N = {}^{2h_n}/_{15^\circ} \quad \textbf{(6)}$$

Where:

N = Photoperiod (hours)

h_n = Angle at time of sunrise (degrees)

6. Corrected adjusted potential evapotranspiration (E_p)

Mather (1977), Ward (1967) state that to improve the accuracy of $\mathbf{E_p}$, correction factors must applied for the length of the month and amount of received insolation (sunshine). Months longer or shorter than 30 days, with sunshine periods of more or less than 12 hours a day are multiplied by the correction factor (Thornthwaite, 1948). Correction factors represented (Table 3.12) for 30°S were applied as trials were located at latitudes ranging from 29°31'45.53"S to 29°33'31.54"S. Modified E_p (cm) can be calculated by multiplying unadjusted E_p by **correction factors** (Table 3.12).

Table 3.12: Correction factors of PE values for the different months

Southern Latitude	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
25°	1.17	1.01	1.05	0.96	0.94	0.88	0.93	0.90	1.00	1.10	1.11	1.18
30°	1.20	1.03	1.06	0.95	0.92	0.85	0.90	0.96	1.00	1.1	1.14	1.21

(Thornthwaite, 1948: modified)

Alternatively E_p *is* calculated **(1)** for a one-month interval of 30 days and a photoperiod of 12 hours day^{-1}. To determine the $\mathbf{E_p}$ for the respective month, the $\mathbf{E_p}$ value must be corrected for the number of days in a month (7) (Pereira *et al.,* 2007).

$$\boldsymbol{ETp = ETp * Cor}$$

$$\boldsymbol{Cor = (ND/30)(N/12)} \qquad \textbf{(7)}$$

Where:

Cor = Corrected $\mathbf{E_p}$ (mm month^{-1})

ND = Number of days for respective month (days)

N = Average photoperiod for the respective month (hours).

7. Available soil water

7.1. Precipitation and E*p* difference

Ward (1967) states that the role of a water budget (derived from precipitation and E_p) is to determine whether sufficient water for crop cultivation exists and not to solely rely on annual precipitation with associated erratic patterns. To determine the water budget, E_p is subtracted from precipitation to record a change in storate or storage ($R - E_p$). The water budget must commence in the month in which precipitation (R) is greater than E_p ($R > E_p$), November – December for Southern African summer rainfall areas.

The next step requires calculating the difference between the actual monthly precipitation and calculated evapotranspiration for each site (8) (Pereira *et al.,* 2007).

$$Difference = P - ETP \quad \textbf{(8)}$$

Where:

P = Actual precipitation (mm month^{-1})

E_p = Potential evapotranspiration (mm month^{-1}).

8. Negative accumulation & soil-water storage capacity

Negative soil water accumulation and available soil water are calculated concurrently. If the difference in precipitation and potential evapotranspiration for the succeeding month is negative, the difference is added to the difference of the preceding month and retained for negative differences. A different approach is applied for positive differences following a sequence of negative differences. Positive values are added to available soil water of the preceding month and this value should not exceed the water storage capacity of the soil. Available soil water value is substituted into Equation **9**, derived from Equation **10,** to calculate the negative accumulation. Available soil water is calculated as a function of preceding and present months' difference in precipitation and potential evapotranspiration. Negative differences are substituted in Equation **10** to determine the available soil water.

$$NEG\ ACUM = CAD * Ln^{\left[\frac{ASW}{CAD}\right]} \quad \textbf{(9)}$$

Where:

NEG ACUM = Negative accumulation (mm month^{-1})

CAD = Soil-water storage capacity (mm)

ASW = Available soil-water (mm)

$$ASW = CADe^{\left[\frac{NEG\ ACUM}{CAD}\right]} \quad \textbf{(10)}$$

Where:

ASW = Available soil-water (mm)

CAD = Soil-water storage capacity (mm)

NEG ACUM = Negative accumulation (mm month^{-1}) (Pereira *et al.,* 2007).

9. Real Evapotranspiration

Real evapotranspiration (ETr) is expressed as a function of positive or negative differences between **real and potential evapotranspiration**. A difference greater or equal to zero results in **potential evapotranspiration recorded as real evapotranspiration**. If the difference is **negative**, the sum of precipitation and change in available soil water for the current and preceding month is calculated as the ETr **(Function 11).**

$$ETr = Prec + (ASW_{cur} - ASW_{prec}) \quad \textbf{(11)}$$

Where:

ETr = Real evapotranspiration (mm month^{-1})

Prec = Precipitation (mm month^{-1})

ASW_{cur} = Available soil-water of current month (mm)

ASW_{prec} = Available soil water of preceding month (mm)

10. Water surplus & deficit

Where available soil water is **equal** to the maximum soil-water storage capacity for a site, water surplus is expressed as the **difference between real and potential** evapotranspiration and the change in available soil-water **(Function 12).**

$$\boldsymbol{Surplus} = (\boldsymbol{Precipitation} - \boldsymbol{ETp}) - (\boldsymbol{ASW_{cur}} - \boldsymbol{ASW_{prec}}) \quad \textbf{(12)}$$

Where:

E_p = Potential evapotranspiration (mm month^{-1})

ASW_{cur} = Available soil-water of current month (mm)

ASW_{prec} = Available soil water of preceding month (mm)

Monthly water deficit (WD) is calculated as the difference in potential (E_p) and real evapotranspiration (ETr) (Function 13).

$$\boldsymbol{Deficit} = \boldsymbol{ETp} - \boldsymbol{ETr} \quad \textbf{(13)}$$ (Pereira *et al.,* 2007).

Where:

E_p = Potential evapotranspiration (mm month^{-1})

ETr = Real evapotranspiration (mm month^{-1})

3.18. CALCULATING BIOMASS AND NUTRIENT EXPORT FOR TRIAL SERIES

3.18.1. ESTIMATING BIOMASS FOR THE TRIAL SERIES

The proportion of N and P remobilized from senescing leaves is greater in eucalypts than annual crops (Grove *et al*., 1996; Specht and Groves, 1996). Concentrations of nutrients are higher in bark than stem-wood and although bark constitutes less than 30% of stem biomass, it contains a higher proportion of total nutrient content (Beadle and White, 1968; Lambert, 1981b). Thus, it is imperative to quantify nutrients concentration contained in the biomass pool, most importantly where N and P may exceed short-term requirements due to seasonal conditions or short-term fertilizer effects. The reservoir of nutrients in biomass may become critical in sustaining growth (Grove *et al.*, 1996).

No direct sampling of harvest residues were undertaken prior to establishment of five trials at Mountain Home, KZN. One trial had to be abandoned because of damage to a residue-

retained replication during preparation of burn treatments. Peer reviewed methodology reported by Dovey (2005) was adequate for purposes of estimating biomass, although it would appear to underestimate when compared to actual results for the Karkloof trial (Du Toit, 2003). Stem-wood, bark and branch biomass (Table 3.13) are estimated from the following:

Step 1: Estimate oven-dry biomass from utilizable volume as the product of oven-dry basic density (column **A**) and stand volume for the relevant species (Dovey, 2005).

Step 2: With stem-wood biomass estimated, bark and branch biomass are derived by multiplying stem-wood biomass by values in column **B** and **C** respectively.

Table 3.13: Ratios to convert timber volume to dry mass

Species	Oven dry density (t m^{-3}) (A)	Bark (t ha^{-1}) (B)	Branches (t ha^{-1}) (C)
E. dunnii	0.536	0.16	0.12
E. grandis	0.450	0.12	0.12

(Dovey, 2005 - modified)

Example (High productivity site - Compt. D01b): Stem volume = 214.03 m^3 ha^{-1} (*E. dunnii*), stem wood, bark and branch biomasses were estimated:

- Stem wood = 214.03 m^3 ha^{-1} x 0.536 t m^{-3} = 114.72. t ha^{-1}.
- Bark biomass = 114.72 t ha^{-1} x 0.160 t ha^{-1} = 18.36 t ha^{-1}.
- Branch biomass = 114.72 t ha^{-1} x 0.12 t ha^{-1} = 13.77 t ha^{-1}.

Combined branch and bark mass of *E. dunnii* was 114% higher than *E. grandis* and species of the previous crop must be factored into calculations when determining a residue management rate for mulching and spreading of slash, whilst burning rates per hectare are less affected by residue load.

Table 3.14: Biomass estimations for stem wood, bark and branches

Trial No.	Previous Species	Area (ha)	Age (years)	DBH (cm)	Dom Ht (m)	Tree Vol. (m^3)	Spha	Vol. ha^{-1} (m^3)	Compt Vol (m^3)	Oven dry density factor (t m^{-3})	Stemwood (t ha^{-1})	Bark factor (t ha^{-1})	Bark (t ha^{-1})	Branch factor (t ha-)	Branch (t ha^{-1})
Trial 1	*E. gran*	14.3	7.01	15.17	21.34	0.141	1133	159.32	2278.26	0.450	71.69	0.120	8.60	0.120	8.60
Trial 2	*E. gran*	11.2	7.09	16.86	24.15	0.202	650	131.42	1471.95	0.450	59.14	0.120	7.10	0.120	7.10
Trial 3	*E.dun*	22.2	8.18	17.44	24.3	0.191	1123	214.03	4751.44	0.536	114.72	0.160	18.36	0.120	13.77
Trial 4	*E.dun*	6.7	12.18	17.36	24.29	0.189	1238	233.93	1567.35	0.536	125.39	0.160	20.06	0.120	15.05

(Blue shade - Data Mondi Planning Department. Source cruised and actual data - 2010)

3.18.2. ESTIMATING NUTRIENT MASS FOR ABOVE GROUND BIOMASS

Dovey (2005) reports that nutrients are lost throughout a rotation with the greatest loss occurring at harvesting. The effect of above ground biomass removal is dependent on nutrient pool sizes, additions and losses of nutrients, and rotation length. Excessive biomass removal on sites with small nutrient pools and rapid growth greatly increases the risk of nutrient depletion and a temporary nutrient deficiency may prevail. Although long-term nutrient pools may be unaffected, short-term (within one rotation) or readily available nutrient pools may be depleted by excessive nutrient removal resulting in a depression in tree growth. A lack of nutrient availability early in the rotation (prior to canopy closure) can reduce growth rates. Readily available nutrient pools are slowly replenished from long-term nutrient pools, fertilisation and natural inputs (Dovey and Smith, 2005). Using calculations derived by Dovey (2005), biomass (t ha^{-1}) and nutrient mass contained in each tree component (kg ha^{-1}) were calculated (Table 3.15, Table 3.16, Figure 3.24, Figure 3.25).

Table 3.15: Trial series nutrient mass for stem-wood and bark (kg t^{-1}) using ratios described by Dovey (2005)

Trial No.	Previous species	Vol. ha^{-1} (m^3)	Stemwood (t ha^{-1})	N ratio stem wood	N (kg ha -1) stem wood	P ratio stem wood	P (kg ha -1) stem wood	K ratio stem wood	K (kg ha -1) stem wood	Ca ratio stem wood	Ca (kg ha -1) stem wood	Mg ratio stem wood	Mg (kg ha -1) stem wood
Trial 1	*E. gran*	159.32	71.69	0.85	**60.94**	0.12	**8.60**	1.04	**74.56**	1.59	**113.99**	0.21	**15.05**
Trial 2	*E. gran*	131.42	59.14	0.85	**50.27**	0.12	**7.10**	1.04	**61.51**	1.59	**94.03**	0.21	**12.42**
Trial 3	*E.dun*	214.03	114.72	0.72	**82.60**	0.14	**16.06**	1.10	**126.19**	1.93	**221.41**	0.77	**88.33**
Trial 4	*E.dun*	233.93	125.39	0.72	**90.28**	0.14	**17.55**	1.10	**137.93**	1.93	**242.00**	0.77	**96.55**
Trial No.	**Previous species**	**Vol. ha^{-1} (m^3)**	**Bark (t ha^{-1})**	**N ratio Bark**	**N (kg ha -1) Bark**	**P ratio Bark**	**P (kg ha -1) Bark**	**K ratio Bark**	**K (kg ha -1) Bark**	**Ca ratio Bark**	**Ca (kg ha -1) Bark**	**Mg ratio Bark**	**Mg (kg ha -1) Bark**
Trial 1	*E. gran*	159.32	8.60	*2.52*	**21.68**	0.53	**4.56**	4.37	**37.60**	9.81	**84.40**	3.11	**26.76**
Trial 2	*E. gran*	131.42	7.10	*2.52*	**17.88**	0.53	**3.76**	4.37	**31.01**	9.81	**69.62**	3.11	**22.07**
Trial 3	*E.dun*	214.03	18.36	*2.37*	**43.50**	0.33	**6.06**	5.27	**96.73**	7.41	**136.01**	3.18	**58.37**
Trial 4	*E.dun*	233.93	20.06	*2.37*	**47.55**	0.33	**6.62**	5.27	**105.73**	7.41	**148.66**	3.18	**63.80**

Table 3.16 Trial series nutrient mass for branches (kg t^{-1}) using ratios described by Dovey (2005)

Trial No.	Previous species	Vol. ha^{-1} (m^3)	Branch (t ha^{-1})	N ratio Branch	N (kg ha -1) Branch	P ratio Branch	P (kg ha -1) Branch	K ratio Branch	K (kg ha -1) Branch	Ca ratio Branch	Ca (kg ha -1) Branch	Mg ratio Branch	Mg (kg ha -1) Branch
Trial 1	*E. gran*	159.32	8.60	2.73	**23.49**	0.27	**2.32**	3.97	**34.16**	3.78	**32.52**	1.28	**11.01**
Trial 2	*E. gran*	131.42	7.10	2.73	**19.37**	0.27	**1.92**	3.97	**28.17**	3.78	**26.83**	1.28	**9.08**
Trial 3	*E.dun*	214.03	13.77	2.89	**39.78**	0.29	**3.99**	4.63	**63.74**	4.25	**58.51**	1.41	**19.41**
Trial 4	*E.dun*	233.93	15.05	2.89	**43.48**	0.29	**4.36**	4.63	**69.66**	4.25	**63.95**	1.41	**21.22**

E. dunnii sites showed the greatest nutrient export (kg ha $^{-1}$) for exchangeable base cations (Ca, Mg and K) (Table 3.14, Table 3.16, Figure 3.24 – 3.26) however, the mean volume ha^{-1} recorded for the two previous *E. dunnii* rotations were already 1.5 times higher than equivalent *E. grandis* compartments, with proportionately higher nutrient export potentials. The four trial sites were generally uniform and variability was likely due to species selection and past silviculture practices (Figure 3.24 – 3.26).

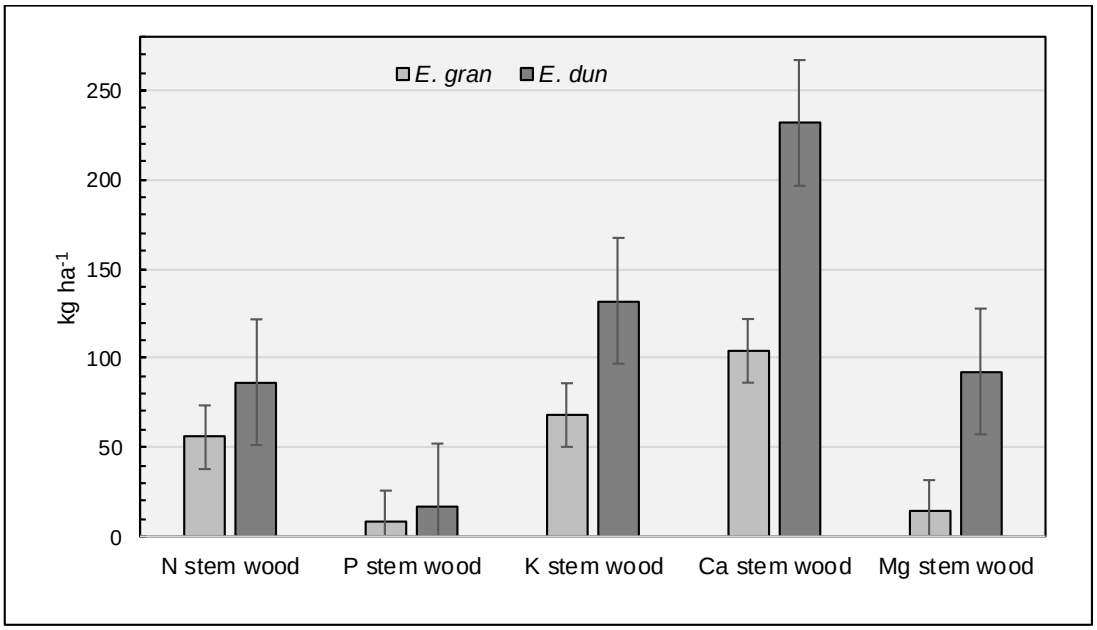

Figure 3.24: Nutrients contained in stemwood for two eucalpyt species (Based on Dovey, 2005). Error bars represent standard error

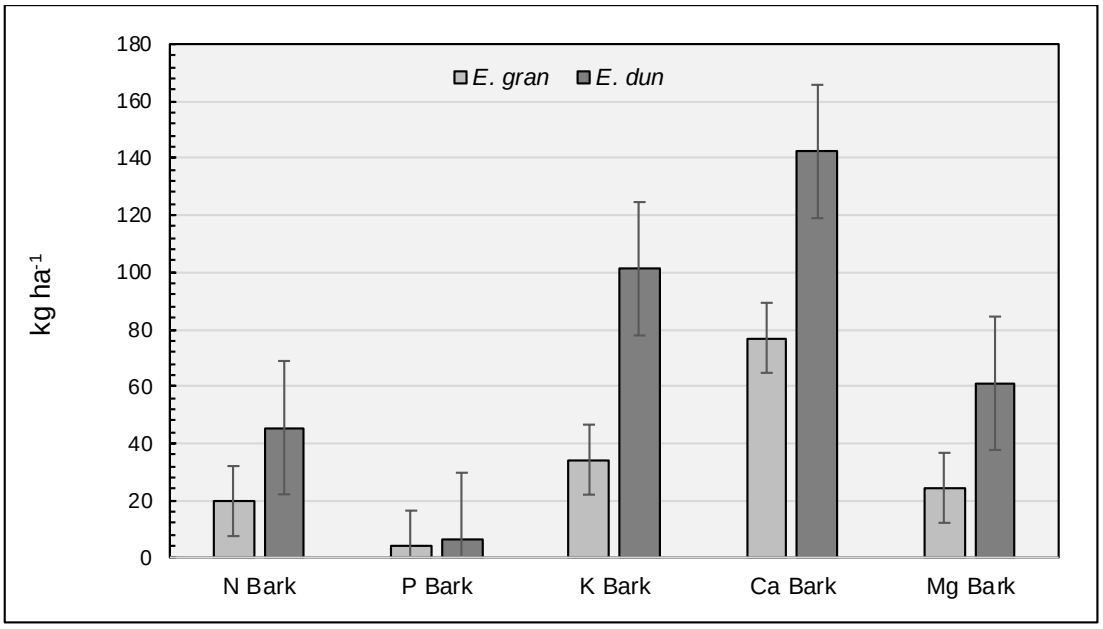

Figure 3.25: Nutrients contained in bark for two eucalypt species (Based on Dovey, 2005). Error bars represent standard error

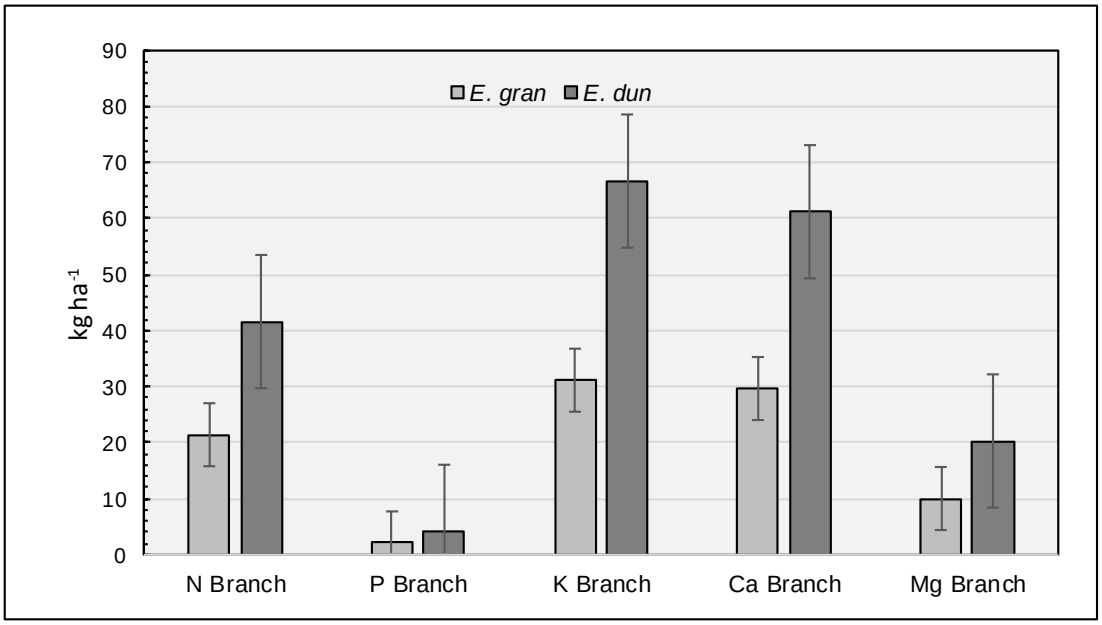

Figure 3.26: Nutrients contained in branches for two eucalypt species (Dovey, 2005). Error bars represent standard error

3.19. TREE SURVIVAL AND GROWTH

Missing trees were recorded at each measurement date, from which changes to stocking treatment per plot could be determined. The initial impacts of treatments on tree growth were determined by measuring tree height (Ht in m) and ground-line diameter (GLD in mm) measurements at planting (0 days), 3, 6 and 12 months after planting. Thereafter, the diameter at breast height (DBH in cm) were measured annually when the trees were over 1.3 m in height, together with height to rotation end. Crown diameters (in m) were assessed

at 1 year to determine the impact of imposed treatments on crown growth (canopy closure). The diameter measurements, together with stocking, calculated basal area (m^2 ha^{-1}) (Elledge and Barlow 2012) as follows:

$$BA = \pi \times \left(\frac{DBH}{200}\right)^2 \times SPH$$

Elledge and Barlow (2012) recommend the prediction of basal area in determining stand density, volume and tree growth, and is the cornerstone for important forest management decisions. Merchantable tree volume (underbark to a top-end diameter of 5 cm) (V in m^3) was determined using volume equations generated for *E. dunnii* and *E. grandis x E. nitens* from site x species matching trials grown in the warm temperate region (ICFR - internal data base). Volume ha^{-1} (Vol in m^3 ha^{-1}) was calculated using mean plot volumes and associated stocking.

3.20. TREE UNIFORMITY

Tree uniformity can influence estimation of tree volume at rotation-end, pulp yield and the efficiency of planning and execution of harvesting operations (Little 1999). Changes in tree uniformity were determined by calculating the coefficient of variance (CV as a %) for GLD and DBH at the plot level:

$$CV = \frac{standard\ deviation}{mean\ diameter}\ x\ 100$$

3.21. DATA ANALYSIS AND INTERPRETATION

Prior to analysis of tree growth variates, the Shapiro-Wilk test for normality and Levene test for stability of variance were applied to check assumptions necessary for a valid analysis of variance (ANOVA) and indicated normality to be within acceptable norms. An ANOVA appropriate for a 3 x 2 x 2 x 2 split-plot design was tested for treatment effects. Only where the *F*-value was significant ($p < 0.05$) were treatment differences further investigated using the Student's *t*-test statistic (least significant differences). All analyses were applied to plot mean data using GenStat® for Windows™ (VSN International 2013). The split-split plot design as applied in this study is uniquely suited for a three-factor experiment where three different levels of precision are required and can be characterised by these important features:

1. Three plot sizes correspond to the three factors, the main plot for the main plot factor, the intermediate plot (subplot) for the subplot factor and the smallest plot (sub-subplot) for the sub-subplot factor.
2. Three levels of precision with the main plot factor receiving the lowest degree of precision and sub-subplot factor receiving the highest degree of precision (Gomez *et al.,* 1984).

The two most common used test procedures for pair comparison in agricultural research are the least significant different (LSD) suited for a planned pair comparison and Duncan's multiple range (DMRT) applicable to an unplanned comparison. Two treatments are deemed significantly different at a prescribed level of significance if their difference exceeds the computed LSD value; otherwise, they are not regarded as significantly different (Gomez *et al.,* 1984). Thus, the LSD test for comparisons of all possible pairs of means could be applied where *F* –test for treatments effect were significant and the number of treatments less than six (Gomez *et al.,* 1984). Only significant main and interaction effects were reported further.Treatments impacts were explained in terms of the following:

a. **Period following planting (0 - 3 months).** Independent inventory checks on stocking and survival have highlighted numerous management shortcomings, with poor technique and nursery plant quality, major contributory factors. The costs of replanting (ca. R13,000/ha) a eucalypt stand in South Africa are extremely high and knock-on effects, over and above operational expenditure, warrant an intervention. At 3 months, a management decision, driven by contractor payments, is applied either to accept a compartment with lower stocking or to replant. The commercial impacts of nursery plant quality, initial stocking, survival and uniformity are reported under the discussion section.

b. **Canopy closure (12 months):** As a function of site and species, canopy closure in short rotation eucalypts usually occurs between 12 - 18 months. From a commercial perspective, 12-months is regarded as the point when further silviculture interventions are no longer practicable. This stage maybe attained earlier or later, but 12 months is a practical management reference point for compartment stocking inventory (5% sample) to determine survival.

c. **Rotation-end (7 - 8 years):** Final rotation measures for height and DBH were possible in 2019. This allowed for accurate calculation of stocking, height, DBH and final standing volume and the opportunity to determine whether site, residue management, nursery conditioning and insecticide played significant roles, jointly or singularly in explaining treatment differences.

d. **A cross-site analysis** conducted for rotation-end data (stocking, Ht, DBH, BA and volume) (Gomez *et al*., 1984) to determine the impact of genotype.

As trials data sets were large, separate trials were analysed and discussed separately in terms of the following:

1. Mean square values and the influence of main effects and interactions in accounting for variability in Gld/Dbh and BA from Day 0 to full rotation. The variability in diameter growth (weather measured at ground level in young transplants or at breast height in older trees) is presented as one combined variable over time on certain graphs.
2. Significant responses within 2 weeks of planting to assess the effects of nursery grading and initial responses to field conditions.
3. Significant responses at 12 months. Canopies were still compact enough to measure and for physiological readings to be determined.
4. Final measures at full rotation.
5. Trials combined and measured at full rotation across species and site.
6. A comparison of absolute and relative values across trial rotation for Gld/Dbh and BA.

Reporting on data focused an early (Day 0), final rotation and across site responses, with ANOVA tests applied to determine treatment effects. Trials were only discussed at 10% confidence levels if three sites were significant at the 5% level and one site at the 10% level, for a measured trait. Measurements significant at the 10% level were expounded upon where they transitioned from not significant (n.s) to the 5% level by rotation end, as an indication that a treatment within a factor had started to become more important. The 90% level is often ignored but it should be considered as it may indicate if further examination into a treatment factor is really important or not. A 90% certainty, especially if preceded by more significant values may indicate that the economic risk of a treatment is actually really low. For example, the application of fertiliser may generate a significant (>95%) initial response but then absolute differences between fertilised and unfertilised treatments could thereafter remain static (albeit with a decrease in relative growth and hence significance). However, companies may still decide to fertilize as the growth increase is sufficient to replace lost nutrients and cover the costs of initial fertiliser application, even where not statistically significant (Little, 2020, pers comm., 22 August).

As a final section, mean squares and absolute and relative differences were reported as they are intrinsically linked. Mean squares were applied to explain variation within samples and how the partitioning of variance in an ANOVA can be used for interpretive purposes, and to explain within/between factor variance. Absolute, relative growth, and changes in MS (all coupled with significance) will with time, track growth responses and give an overall interpretation of treatment factors (when they are important, for how long they are important as well as differences between site productivities and/or species).

3.22. ABSOLUTE AND RELATIVE VALUE SCORES

Little (2014) states that three factors are important when comparing treatment impacts, including magnitude or size of response, timing of the response and duration or length of that response. Absolute differences reflect those differences between two treatments whilst the relative treatment difference can best described as the difference between two treatments divided by the standard operational treatment. To explain absolute versus tree growth response, a scenario (Figure 3.27, Table 3.17) is expounded based on work by Little (2014). The scenario illustrates where an initial treatment has an impact but significance decreases with time. Between Time 1 and Time 2, there is a treatment response as lines diverge. After Time 2, the lines stay equally apart, absolute difference is constant, and treatment no longer has an effect; however, the relative differences decreases as trees grow large thus significance become weaker with time (Table 3.17).

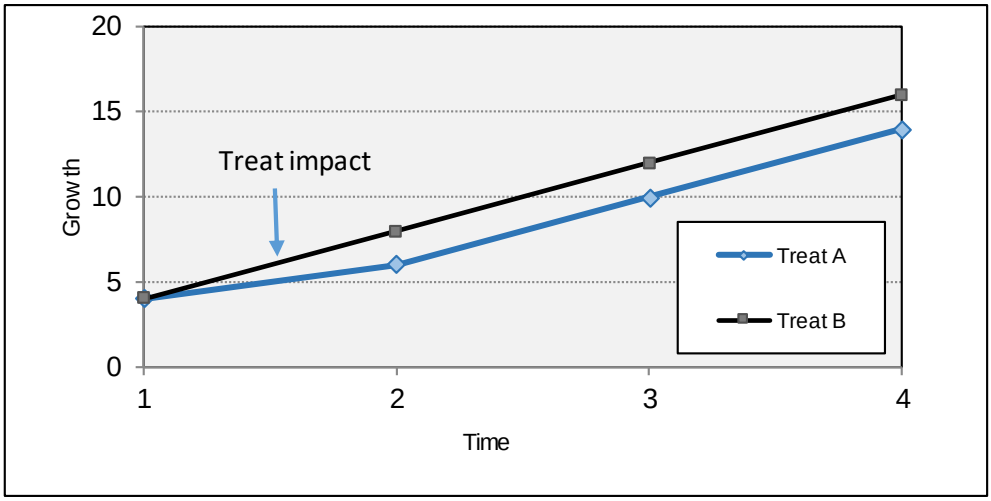

Figure 3.27: Absolute vs. Relative tree growth response. Scenario 1: Initial treatment impact, but significance decreases with time (Little, 2014)

In terms of explaining relative difference, the difference between Treatment A and B for Period 1 would equal the absolute difference (Treatment B – Treatment A; 4 – 4 = 0). The relative difference (%) equals the absolute difference divided by Treatment A (0/4 = 0.0%). For Period 2, the absolute difference = 2 (Treatment B - Treatment A; 8 - 6 = 2). The relative difference (%) = absolute difference divided by Treatment A (2/6 = 33.3%) with a strong significance. At Period 3, the absolute difference = 2 but the treatment differences had declined and hence relative difference = 20.0%, no longer significant for the purposes of this explanation.

Table 3.17: Explaining absolute vs. relative tree growth response. Scenario – Initial treatment response with significant growth decline over time

	Period 1	Difference (Diff: Period 2 - 1)	Period 2	Difference (Diff: Period 3 - 2)	Period 3	Difference (Diff: Period 4 - 3)	Period 4
Treatment A	**4**	**2**	**6**	**4**	**10**	**4**	**14**
Absolute difference (Treat B - Treat A)	0		2		2		2
Relative difference (Absolute diff./Treat A)	0.00%		33.33%		20.00%		14.29%
Significance	ns		**		*		ns
Treatment B	**4**	**4**	**8**	**4**	**12**	**4**	**16**

Little (2014) – modified

The above scenario would be typical of a Type 1 growth response whereby the stand develops through a phase of early rapid growth but this does not affect potential productivity; e.g. weed control, fertilisation, site preparation, tree protection (Little, 2014).

CHAPTER 4: RESULTS

4.0. SOIL ANALYSIS

4.0.1. HIGH PRODUCTIVITY SITE (D010): *E. DUNNII*

Clay contents for the Magwa 1100 soil form (A and B-horizons) ranged from 25 - 35% (Table 4.1), fairly consistent with the findings of Fey (2010) or Du Toit (2003) for similar soils. A and B-horizon silt content varied from 26 – 36%, whilst sand content ranged from 14 – 21% (Table 4.1). N concentrations were 0.4% (A-horizon) and 0.2% (B-horizon) (Table 4.2) and equal to results for the Karkloof trial, approximately 18 km north of this site (Table 4.3) (Du Toit, 2003). The pH (KCl) values for the A-horizon showed little variation (pH = 4.0), irrespective of residue treatment, and corresponded closely with findings of Du Toit (2003). B-horizon pH values (KCl) = 4.3 were supported by Karkloof trial results = 4.2 (Du Toit, 2003).

Mean pH (H_2O) for A-horizon samples (pH = 4.2) were consistent with the Karkloof results (pH = 4.3 - Du Toit, 2003), whilst mean B-horizon pH across treatments (pH = 4.5) were marginally less acidic than Karkloof (pH = 4.8 - Du Toit, 2003). Fey (2010) states that the relatively small difference in values (KCl vs. H_2O) suggests that the B-horizon possessed sufficient positive charge to make NO_3^- retention an important plant nutrient supply property. Interestingly, all NO_3^- levels in the B-horizon were generally higher than the A-horizon (double concentration) for spread and mulched treatments but not so for the burn treatment. This was possibly due to a temporary N 'draw-down' resulting from an imbalance in the C: N ratio in the initial stages as residues decomposition commenced. Unfortunately, C was not measured for the Mountain Home trial series but C: N ratios calculated by Du Toit (2003) for the Karkloof trials ranged from 20.4 – 23.7 (Table 4.3), much higher than that of 11.0 – 13.0 recorded in the tropics (Du Toit, 2003). De Barros and De Novais (1996) report a preferential absorption of NH_4^+ as opposed to NO_3^-.

The cation exchange capacity (CEC) is a measure of adsorbed cations that can be displaced by exchange with other cations, expressed as milliequivalents per 100 g (meq 100 g^{-1}) soil (Reganold *et al.,* 1985). Cation exchange is now more frequently reported as cmol (+) kg^{-1} (SI unit) or the amount of charge per unit mass of soil, or mole (mol). To maintain consistency of charge, irrespective of the cation, we refer to the fraction of the ion that possesses one mol of charge (Reganold *et al.,* 1985) where 1 cmol kg^{-1} is equal to 1 meq 100 g^{-1}. Exchangeable Ca levels for burn and mulch treatments, A and B-horizons, were 0.01 cmol kg^{-1}, whilst Ca levels for the spread treatment were higher at 0.04 cmol kg^{-}

^{1} (A-horizon) and 0.03 cmol kg^{-1} (B-horizon) (Table 4.1). Du Toit (2003) recorded a higher exchangeable Ca = 0.4 cmol kg^{-1} for the Karkloof trials. The lower exchangeable Ca may have been due to more acidic conditions and subsequent binding of exchangeable cations. Maximum exchangeable Mg and K levels = 0.11 cmol kg^{-1} (A-horizon), with B-horizon (Table 4.1) exchangeable K = 0.07 cmol kg^{-1}, in line with findings at Karkloof (K = 0.1 cmol kg^{-1} - Du Toit, 2003). Exchangeable Na (A-horizon) was 0.10 cmol kg^{-1}, whilst B-horizon levels did not exceed 0.2 cmol kg^{-1} with both measures in line with literature findings (Fey, 2010), (Du Toit, 2003). A-horizon organic carbon (O.C) was of moderately high concentration at 2.4 % for all residue treatments

Table 4.1: High productivity site (D010). Soil chemical properties - A and B horizons

Treat	Horizon	pH (KCL)	pH (H_20)	Ca	Mg	K	Na
				Exchangeable cations ($cmol_c\ kg^{-1}$)			
Burn	A	4.07	4.25	0.01	0.08	0.09	0.10
Burn	B	4.31	4.49	0.01	0.08	0.06	0.12
Mulch	A	4.08	4.23	0.01	0.07	0.09	0.12
Mulch	B	4.44	4.64	0.01	0.07	0.07	0.15
Spread	A	4.04	4.27	0.04	0.11	0.11	0.10
Spread	B	4.36	4.60	0.03	0.12	0.06	0.14

Table 4.2: High productivity site (D010). Soil chemical properties - A and B horizons

Treat	Horizon	S – value	P mg kg^{-1}	N %	NH_4 - N mg kg^{-1}	NO_3 - N mg kg^{-1}	Al mg kg^{-1}	Ex. acid $cmol_c kg^{-1}$	Conductivity µS/cm	FM%	Sum of Bases	CEC $cmol_c$ kg^{-1}
Burn	A	0.28	2.15	0.36	12.64	27.71	144.98	2.59	86.45	36.73	0.28	2.87
Burn	B	0.27	1.64	0.21	13.25	25.45	44.18	0.90	66.70	36.51	0.27	1.17
Mulch	A	0.29	2.00	0.35	11.52	20.60	147.63	2.36	87.05	41.41	0.29	2.65
Mulch	B	0.29	1.61	0.17	13.05	28.74	27.76	0.61	81.88	37.26	0.3	0.91
Spread	A	0.36	2.04	0.33	12.57	22.76	141.36	2.26	79.13	42.19	0.36	2.62
Spread	B	0.35	1.64	0.18	11.85	24.50	29.06	0.65	71.10	37.39	0.35	1.00

N%: Total Kjedahl nitrogen

Table 4.3: Karkloof trial series - Soil properties prior to trial establishment

Depth (cm)	Bulk density ($mg\ m^{-3}$)	pH (KCl)	pH (H_2O)	C	N	C:N	P (mg kg^{-1}	Exchangeable cations (1 meq/100 g = 1 $cmol_c$ kg^{-1})				Sum of bases	Extr. acidity	Effective CEC
				($g\ kg^{-1}$)				Ca	Mg	K	Na			
0-20	0.9	3.94	4.33	66.5	3.2	21.3	2.75	0.43	0.64	0.16	0.23	1.46	3.25	4.71
20-40	1.21	4.23	4.87	42.3	1.8	23.7	0.94	0.33	0.56	0.11	0.21	1.20	1.48	2.68
40-60	1.35	4.40	5.13	23.5	1.2	20.4	0.34	0.31	0.55	0.09	0.21	1.16	0.81	1.97

(Modified Du Toit, 2003)

Extractable P in the A-horizon (2.2 mg kg^{-1}) and B-horizon (1.6 mg kg^{-1}) did support the relatively immobile nature of P with a higher concentration in the A-horizon (Table 4.2).

Extractable P in the Karkloof trials (Du Toit, 2003) showed the expected trend of a higher figure in the A-horizon (2.8 mg kg^{-1}), followed by rapidly decreasing concentrations down to 0.34 mg kg^{-1} at 60 cm (B-horizon), as P became increasingly immobilized. Fey (2010) states that such a soil form has an elevated P fixing capacity and is likely to show strong buffering capacity when limed due to the high humus content.

The sum of bases or base saturation was calculated (Table 4.2) by summing exchangeable Ca, Mg, Na and K cmol kg^{-1} (MacVicar and De Villiers, 1991). Both sum of bases and CEC were markedly lower in the high productivity site (Table 4.1) as compared to the Karkloof trials (Du Toit, 2003). This was expected as experimental sites at Mountain Home Estate received higher mean annual rainfall than that of Karkloof. The soils are thus likely to be more highly leached with a higher acid saturation than the soils of Karkloof. Al levels for A-horizons across all three treatments were not significant but varied between A and B-horizons (Table 4.2). Al concentration in the A-horizons were 3 to 5 times higher than the coinciding B-horizon for the same treatment, varying from 141.0 – 148.0 mg kg^{-1}, whilst Fey (2010) reports levels of up to 180.0 mg kg^{-1}. Al concentrations in the B-horizon decreased to 28.0 - 44.0 mg kg^{-1} across treatments, whilst Fey (2010) records up to 160 mg kg^{-1} in the same horizon. Al concentrations for the high productivity trial showed a strong linear correlation (r = 0.9) between Al and exchangeable acidity. Al concentration increase was associated with strongly acidic upper horizons and extremely low levels of exchangeable cations. Exchangeable Al were only half as concentrated as the medium productivity trial site (E013). De Barros and De Novais (1996) report a high Al tolerance for eucalypts due to evolution on sites with very high Al concentrations. However, countering the Al toxicity to the roots does come with a cost of assimilated C to the tree (Rocha *et al.*, 2019).

4.0.2. MEDIUM PRODUCTIVITY SITE (E013): *E. DUNNII*

The clay content of the A-horizon (Magwa 1100 and Inanda 1100) varied from 25 - 30%, whilst B-horizon clay content ranged from 30 - 35%. Silt percentage (A-horizon) ranged from 41 - 45%, with B-horizon silt varying from 30 - 34%. Texture was classified as sandy clay loam with the higher silt percentage possibly due to accumulation of silt washed downslope. Sand percentages for A-horizons ranged from 13 - 20% and B-horizon between 14 - 16% (Table 4.4).

Table 4.4: Medium productivity site (E013). Soil chemical properties - A and B horizons

Treat	Horizon	pH (KCL)	pH ($H_2$0)	Ca	Mg	K	Na
				Exchangeable cations ($cmol_c\ kg^{-1}$)			
Burn	A	3.94	4.22	0.01	0.11	0.10	0.13
Burn	B	4.15	4.51	0.01	0.07	0.06	0.14
Mulch	A	3.97	4.14	0.02	0.08	0.07	0.12
Mulch	B	4.11	4.42	0.02	0.06	0.05	0.14
Spread	A	3.98	4.28	0.01	0.10	0.08	0.12
Spread	B	4.13	4.61	0.01	0.07	0.07	0.15

N concentration (%) ranged from 0.2 - 0.4% (Table 4.5), whilst pH (KCl) values for A and B-horizons were close to reported literature, Fey (2010) and Du Toit (2003), at 4.0 and 4.1 respectively. The pH (H_2O) for A-horizon samples varied slightly from 4.1 - 4.3 and equal the findings of Du Toit (2003) for the Karkloof trials. Mean B-horizon pH ($H_2$0) varied from 4.4 - 4.6 across all treatments and were once again very similar to the Karkloof trials (Du Toit, 2003). Lower pH for this trial could be attributed to increased leaching as a result of the high rainfall for the site (>1100 mm). Fey (2010) adds that very low base reserves and high acidity can be partly attributed to long term commercial forestry activities that may exacerbate cation stripping.

Exchangeable Ca levels across horizons and three treatments did not exceed 0.02 $cmol_c\ kg^{-1}$ (Table 4.4) whilst Fey (2010) and Du Toit (2003) report 0.1 cmol kg^{-1} and 0.4 $cmol_c\ kg^{-1}$ respectively. Exchangeable Mg and K varied from 0.06 - 0.1 $cmol_c\ kg^{-1}$ (Table 4.4), with exchangeable Na not exceeding 0.1 $cmol_c\ kg^{-1}$. All exchangeable cation levels were close to cited literature (Du Toit, 2003) for associated soil forms. Organic carbon (A-horizon) at 1.9% was representative for similar sites (Fey, 2010).

Table 4.5: Medium productivity site (E013). Soil chemical properties - A and B horizons

Treat	Horizon	S – value	P mg kg^{-1}	N %	NH_4 - N mg kg^{-1}	NO_3 - N mg kg^{-1}	Al mg kg^{-1}	Ex acid $cmol_c$ kg^{-1}	Conductivity µS/cm	FM%	Sum of Bases	CEC $cmol_c$ kg^{-1}
Burn	A	0.36	1.83	0.42	6.36	15.03	242.94	4.04	99.28	42.72	0.35	4.39
Burn	B	0.28	1.32	0.20	5.76	5.76	95.63	1.67	48.38	35.43	0.28	1.95
Mulch	A	0.28	1.98	0.44	5.80	19.00	323.72	4.74	84.05	49.17	0.29	5.03
Mulch	B	0.26	1.16	0.26	5.66	9.46	135.24	2.36	55.63	41.17	0.27	2.63
Spread	A	0.38	1.68	0.42	5.60	15.38	211.63	4.25	80.18	47.46	0.31	4.56
Spread	B	0.30	0.99	0.23	5.45	5.99	88.97	2.02	39.35	40.90	0.30	2.32

OC (WB): Organic carbon (Walkley-Black); N %: Total Kjedahl nitrogen

A-horizon extractable P varied from 1.7 – 2.0 mg kg^{-1} (Table 4.5) with results similar to Du Toit (2003) at 2.8 mg kg^{-1}. B-horizon P varied from 1.0 - 1.3 mg kg^{-1} whilst Fey (2010) reports 0.5 mg kg^{-1} and Du Toit (2003) as low as 0.34 mg kg^{-1}. The levels of P across treatments (Table 4.5) were not significantly different but B-horizon samples were consistently lower than A-horizon, reflecting the immobile nature of P. Al concentrations (A-horizon) across three treatments varied from 212 - 324 mg kg^{-1} (Table 4.5), whilst Fey (2010) records concentrations as high as 250.0 mg kg^{-1}. B-horizon Al decreased to 135 mg kg^{-1} across treatments versus 110 mg kg^{-1} in cited literature (Fey, 2010). Al concentrations for the trial were high and could be associated with strongly acidic upper horizon and lower levels of exchangeable cations.

4.0.3. HIGH PRODUCTIVITY SITE (D01B): *E. GXN*

A Kranskop 1100 soil form with a fine sandy clay loam texture dominated the whole trial site, characterized by humus rich, freely draining and low base status characteristics. A-horizon clay content (Table 4.6) = 35% with B-horizon clay close to 45%. Silt (A-horizon) samples ranged from 32 - 48% (mean = 43%) with sand percentages up to 13% (Table 4.6).

The pH (KCL values) for A and B-horizons were similar to cited literature (Du Toit, 2003) at 4.1, with mean pH (H_2O) for A and B-horizon samples (4.5 – 4.7) reflecting similarities to the literature (Fey, 2010; Du Toit, 2003). Exchangeable Ca was higher than previous trials at 0.3 - 0.6 $cmol_c$ kg^{-1} (Table 4.6), whilst Du Toit (2003) reports 0.4 $cmol_c$ kg^{-1}.

Table 4.6: High productivity site (D01b). Soil chemical properties - A and B horizons

Treat	Horizon	pH (KCL)	pH (H_20)	Ca	Mg	K	Na
				Exchangeable cations ($cmol_c\ kg^{-1}$)			
Burn	A	3.80	4.54	0.35	0.29	0.08	0.04
Burn	B	4.03	4.22	0.06	0.08	0.11	0.03
Mulch	A	3.98	4.87	0.48	0.21	0.14	0.03
Mulch	B	4.16	4.49	0.38	0.25	0.12	0.03
Spread	A	4.10	4.81	0.06	0.10	0.07	0.03
Spread	B	4.16	4.86	1.35	0.46	0.13	0.04

Maximum Mg and K levels were 0.3 $cmol_c\ kg^{-1}$ and 0.1 $cmol_c\ kg^{-1}$ (Table 4.6) whilst Na never exceeded 0.03 cmol kg^{-1}. All exchangeable cation levels coincided with Fey (2010) but were lower than findings by Du Toit (2003). Organic carbon (A-horizon) = 2.5%.

Table 4.7: High productivity site (D01b). Soil chemical properties - A and B horizons

Treat	Horizon	S – value	P mg kg^{-1}	N %	Al mg kg^{-1}	Ex acid $cmol_c\ kg^{-1}$	Conductivity µS/cm	FM%	Sum of Bases	CEC $cmol_c\ kg^{-1}$
Burn	A	0.75	0.50	0.25	143.76	3.33	22.77	33.19	0.75	4.07
Burn	B	0.29	0.50	0.16	82.04	1.52	47.70	32.01	0.29	1.80
Mulch	A	0.85	0.50	0.40	128.18	3.05	37.50	34.64	0.85	3.90
Mulch	B	0.78	0.50	0.19	48.17	1.13	49.55	35.82	0.78	1.92
Spread	A	0.26	1.50	0.37	92.73	2.38	39.40	32.08	0.26	2.63
Spread	B	1.97	0.50	0.19	49.15	1.30	47.75	32.70	1.97	3.27

OC (WB)**:** Organic carbon (Walkley-Black); N %**:** Total Kjedahl nitrogen

A-horizon mean extractable P = 0.8 mg kg^{-1} (Table 4.7), with Du Toit (2003) recording a figure 3.5 times higher for the Karkloof trials. Spread residue revealed the highest P levels (A-horizon), some three times more than much or burn treatments (Table 4.7). Mean P concentrations (B-horizons) were 0.5 mg kg^{-1}, equivalent to cited literature (Fey, 2010; Du Toit, 2003). Al concentrations (A-horizon) showed the highest levels in the burn treatment (144 mg kg^{-1}) with the lowest in spread residues at 93 mg kg^{-1} (Table 4.7). B-horizon levels of Al decreased to 82 mg kg^{-1} for the burn treatment and only 48 mg kg^{-1} in mulch. Al concentrations for this trial were much lower than previous trials and could be associated with less acidic conditions in the upper horizon and concomitantly higher concentrations of base cations.

4.0.4. MEDIUM PRODUCTIVITY SITE (F026): *E. GXN*

This trial was dominated by fine sandy clay loam Inanda 1100 and Kranskop 1100 soil forms with mean A-horizon clay content (Table 4.8) = 35% and silt (A-horizon) samples with a mean = 30%. Topography for the trial was flat with slope at under 5%. Mean sand percentage for A-horizon samples = 20%.

Table 4.8: Medium productivity site (F026) - Soil chemical properties - A and B horizons

Treat	Horizon	pH (KCL)	pH (H_20)	Ca	Mg	K	Na
				Exchangeable cations			
				($cmol_c kg^{-1}$)			
Burn	A	3.83	4.67	0.12	0.14	0.08	0.03
Burn	B	3.99	4.42	0.22	0.19	0.11	0.03
Mulch	A	3.94	4.55	0.14	0.09	0.09	0.03
Mulch	B	3.93	4.50	0.20	0.15	0.09	0.03
Spread	A	3.87	4.43	0.06	0.08	0.06	0.02
Spread	B	3.91	4.39	0.12	0.11	0.09	0.02

Mean pH (KCL values) for A and B-horizons were equal and close to those cited in literature (Fey, 2010; Du Toit, 2003) at 4.0 and 4.1 respectively. Mean pH for A-horizon (H_2O = 4.6) and B-horizon (H_2O = 4.4) samples were also very close (Fey, 2010; Du Toit, 2003). Exchangeable Ca concentration = 0.2 $cmol_c kg^{-1}$ (Table 4.8) were similar to the Karkloof trial of 0.4 $cmol_c kg^{-1}$ (Du Toit, 2003). All B-horizon samples reflected concentrations of up to 1.7 times higher than A-horizon equivalents, something not previously noted in earlier trials for apedal soils. Significant treatments differences for Ca concentration were not evident from early soil analysis; however, samples were analysed within 6 months of trial establishment to determine whether exchangeable cation concentrations correlated with residue treatments.

Maximum Mg and K levels were 0.2 $cmol_c kg^{-1}$ and 0.1 $cmol_c kg^{-1}$ (Table 4.8) respectively and Na never exceeded 0.03 $cmol_c kg^{-1}$. All exchangeable cation levels were similar to literature reported by Fey (2010) but lower than Du Toit (2003). Organic carbon (A-horizon) = 2.2%.

Table 4.9: Medium productivity site (F026). Soil physical and chemical properties - A and B horizons

Treat	Horizon	S – value	O.C. (WB) %	P mg kg^{-1}	N %	Al mg kg^{-1}	Ex acid $cmol_c kg^{-1}$	Conductivity µS/cm	FM%	Sum of Bases	CEC $cmol_c kg^{-1}$
Burn	A	0.37	5.83	0.45	0.27	133.87	3.70	26.50	24.69	0.37	4.06
Burn	B	0.55	3.05	0.50	0.18	66.63	1.67	52.30	23.58	0.55	2.22
Mulch	A	0.35	4.45	0.53	0.25	112.14	2.61	35.75	22.15	0.35	2.96
Mulch	B	0.47	4.00	0.50	0.24	102.89	2.81	48.20	23.28	0.47	3.28
Spread	A	0.22	4.72	0.50	0.22	117.30	2.90	28.65	22.17	0.22	3.12
Spread	B	0.34	4.56	0.40	0.23	114.91	2.58	31.60	28.15	0.34	2.92

OC (WB): Organic carbon (Walkley-Black); N %: Total Kjedahl nitrogen

A-horizon mean extractable P = 0.5 mg kg^{-1} (Table 4.9), whilst B-horizon, P concentrations were 0.5 mg kg^{-1} and equal to cited literature (Fey, 2010; Du Toit, 2003). Residue management had very little impact on soil chemistry. One usually notices elevated pH and based cations after burning. Waiting time prior to burning may have allowed accelerated soil processes to mask these effects and hence variability would also be high. The levels of P across treatments (Table 4.9) were not significantly different across treatment or solum. Al concentrations (A-horizon) across three treatments once again showed the highest level (134 mg kg^{-1}) in the burn treatment, with spread residue and mulching similar. Al concentrations in the B-horizon decreased to 95 mg kg^{-1} across treatments with overall levels for the trial lower than the previous three, possibly associated with less acidic conditions in the upper horizon.

4.1. TRIAL WATER DEFICIT

Water deficits for four trial sites were based on long-term climate data sourced from the Cedara Agriculture Research Centre, collated for the period 2010 – 2019 (ARC 2020). Water stress in climates that are typically subtropical, humid with dry winters and warm to hot summers tend to hamper timber productivity. Rainfall is generally unevenly distributed during the year with 4 – 5 months of water deficit (Table 4.11) (Alvares *et al*., 2013), and hence scientific consensus that timber plantation productivity is limited by water availability (Stape *et al*., 2004). Climate description for the four trials sites is described as warm temperate, Cfb – Köppen – Geiger class, more specifically warm temperate, fully humid, warm summer (https://en.climate-data.org, 2020). Rainfall distribution is uneven with water stress medium to high. Mean plant available water (PAW) (Table 4.10) was verified for each trial site based on soil form, texture class, clay % (A horizon) and effective rooting depth. Three of four trials showed uniform PAW distribution with only the medium productivity site planted to *E. dunnii* (E013) showing some degree of soil moisture variability due to variable

soil depths on the trial sites. Climate data for mean monthly temperature (°C), mean monthly rainfall (mm) and mean total relative evapotranspiration (ETO as mm) are summarised (Table 4.11).

Table 4.10: Plant available water (PAW) summary for trial sites

Site	Productivity (stand volume)	Species	Weighted Mean PAW	Accuracy of PAW	Remarks
D01b	High	*E. gxn*	108	High	Uniform for all plots
D010	High	*E.dunnii*	36	High	Few plots at higher PAW
E013	Medium	*E.dunnii*	47	Variable	PAW range from 32 – 116.
F026	Medium	*E. gxn*	81	High	PAW range from 71 - 95

Table 4.11: Trial climate data (2010 – 2019) - Cedara Agriculture Research Station

Mean monthly temperature (°C)	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Average
1	20.63	20.49	21.42	20.99	21.67	21.30	21.20	19.92	20.58	20.14	20.83
2	21.83	21.20	21.99	20.99	21.94	20.07	21.52	20.14	20.83	20.28	21.08
3	20.39	21.97	19.53	19.47	20.13	20.01	20.76	19.81	19.62	20.27	20.19
4	18.00	16.16	15.95	16.60	16.67	16.36	18.49	16.95	18.32	17.41	17.09
5	16.05	14.31	15.45	14.07	15.54	15.82	14.64	15.00	14.30	16.07	15.12
6	11.90	10.99	11.86	12.27	12.69	11.88	12.98	12.98	12.33	12.64	12.25
7	12.37	9.49	12.04	12.64	11.64	12.19	11.35	12.89	11.66	13.29	11.95
8	13.58	12.67	14.41	13.61	14.92	15.75	14.34	13.48	13.08	14.87	14.07
9	17.36	16.55	15.01	15.36	17.66	16.68	16.24	17.00	15.68	16.11	16.36
10	17.45	17.24	16.67	16.78	15.94	19.42	16.21	15.92	15.73	18.53	16.99
11	19.21	17.76	17.46	18.98	17.41	17.98	17.90	17.34	17.58	19.32	18.09
12	18.90	19.62	20.59	18.79	19.69	21.80	20.75	18.00	20.83	18.96	19.79
Monthly Rainfall (mm)	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**Average**
1	140.73	102.62	98.04	122.68	97.78	118.61	158.25	85.42	65.35	57.41	104.69
2	97.29	74.16	44.7	130.55	96.01	72.39	115.83	226.32	227.6	123.19	120.80
3	184.45	114.05	89.66	73.4	239.52	83.32	95.51	64	155.7	61.47	116.11
4	67.3	82.8	20.57	109.47	16.76	58.17	20.07	76.45	64.77	111	62.74
5	3.3	48.26	18.29	33.78	1.52	5.33	18.54	74.68	38.1	24.13	26.59
6	5.08	23.11	7.11	9.65	4.06	0	2.29	0.25	1.78	0	5.33
7	1.78	70.61	8.64	2.79	2.29	42.42	63.75	0	19.81	0.76	21.29
8	2.79	34.54	94.99	16.51	3.56	2.79	40.13	4.83	41.4	7.62	24.92
9	4.57	35.3	163.58	20.57	49.79	42.67	45.47	11.94	53.34	19.81	44.70
10	84.33	57.15	147.57	107.7	87.89	24.89	75.19	145.29	61.47	29.97	82.15
11	121.92	123.18	105.66	105.16	132.58	54.1	87.38	135.64	40.89	131.31	103.78
12	134.37	112.27	121.42	138.42	124.46	84.59	34.04	98.3	147.32	116.58	111.18
Cedara annual rainfall	**847.91**	**878.05**	**920.23**	**870.68**	**856.22**	**589.28**	**756.45**	**923.12**	**917.53**	**683.25**	**830.24**
Hilton annual rainfall	**1187**	**1403**	**1436**	**1381**	**1213**	**1074**	**1217**	**1142**			**1256.63**
Mean Evapotranspiration (ETO)	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**Average**
1	90.78	98.79	112.39	115.13	128.71	128.31	108.33	123.87	115.82	115.91	113.80
2	104.61	104.07	94.4	106.53	113.52	101.81	105.97	100.05	98.87	101.45	103.13
3	91.35	99.46	91.51	90.84	100.95	99.9	104.84	119.52	94.37	104.33	99.71
4	70.77	66.06	91.38	83.22	86.82	76.98	85.91	96.39	75.38	73.19	80.61
5	70.56	57.09	71.67	66.35	72.65	72.78	67.67	75.37	65.47	76.22	69.58
6	55.26	51.82	61.17	64.67	63.56	61.06	59.31	67.2	61.88	66.12	61.21
7	64.36	51.55	73.52	60.16	70.2	61.45	63.58	71.42	63.81	77.78	65.78
8	82.64	73.18	85.41	86.27	87.95	84.13	96.16	84.19	67.71	81.46	82.91
9	96.9	84.42	80.04	92.77	112.04	84.63	88.44	100.26	92.68	106.87	93.91
10	86.11	93.62	79.91	104.59	88.54	123.09	93.38	105.17	111.24	129.08	101.47
11	86.8	87.19	90.16	113.77	83.15	111.31	88.82	48.42	112.91	104.75	92.73
12	88.75	88.21	118.63	96.92	107.32	127.93	131.92	97.7	121.26	110.95	108.96

Long terms rainfall measured at Hilton was consistently higher than the Cedara Research Centre data although distance between weather stations did not exceed 4 km. The cause of the gradient from a higher MAP at Hilton (South) towards Cedara (North) was most likely orographic in nature; however, all trials were equidistant to both rainfall-measuring sites.

Mean heat index (I) values based on historical mean temperatures for each month over the rotation, 2010 to 2019, were calculated (Table 4.12). The monthly thermic effect for a year (summed), $I = 77.389$ with a cubic function value $a = 1.7296$. Calculations were as described in materials and method section based on Thornthwaite (1948).

Table 4.12: Heat Index calculation based on mean monthly temperature (°C) - Trial climate data for full rotation (2010 to 2019) - Cedara Agriculture Research Station

M	Temp (Tn).	Heat index
1	20.8	8.6753406
2	21.1	8.8306024
3	20.2	8.2759377
4	17.1	6.4279603
5	15.1	5.3412673
6	12.3	3.8832688
7	12.0	3.7420921
8	14.1	4.7888358
9	16.4	6.0187694
10	17.0	6.370528
11	18.1	7.0068271
12	19.8	8.0277707
Heat Index	***I***	**77.3892**
	Cubic function of *a*	**1.7296829**

Solar azimuth (δ), the projected angle of the sun relative to the position in the plane of the local horizon, angle at time of sunrise (h_n) (°) and photoperiod hours (N) for each day of the month (one year) were calculated (Table 4.13) based on Thornthwaite (1948). Average photoperiod hours varied from 10.1 (June – mid winter) to 13.9 hours December – midsummer. Only 12 days of month 1 (January) are included (Table 4.13) for solar azimuth and angle at time of sunrise whilst average photoperiod was calculated and presented for 12 months.

Table 4.13: Solar azimuth (δ), angle at time of sunrise (h_n) (°) and photo-period hours (N) for trials at Hilton, KZN (Thornthwaite, 1948)

Month	Latitude	NDA (day number of year	Solar azimuth (degrees) δ	Angle at time of sunrise (°) h_n	Photoperiod (hours) N	Month	Average N (hours/day)
1	-29.5419	1.00	-22.9305	103.8721	13.84962	1	13.648
1	-29.5419	2.00	-22.8427	103.8117	13.84156	2	13.005
1	-29.5419	3.00	-22.7480	103.7467	13.83289	3	12.151
1	-29.5419	4.00	-22.6466	103.6772	13.82363	4	11.244
1	-29.5419	5.00	-22.5385	103.6032	13.81376	5	10.494
1	-29.5419	6.00	-22.4237	103.5249	13.80331	6	10.133
1	-29.5419	7.00	-22.3023	103.4421	13.79228	7	10.329
1	-29.5419	8.00	-22.1742	103.3550	13.78067	8	10.997
1	-29.5419	9.00	-22.0396	103.2637	13.76849	9	11.879
1	-29.5419	10.00	-21.8985	103.1682	13.75576	10	12.784
1	-29.5419	11.00	-21.7509	103.0685	13.74246	11	13.527
1	-29.5419	12.00	-21.5968	102.9647	13.72863	12	13.868

Solar azimuth (degrees) δ and angle at time of sunrise (°) h_n illustrated for 12 days - month 1

Mean annual precipitation (MAP as mm) and water deficits (WD as mm y^{-1}) are presented (Table 4.14) for the four trial sites. Each site is described for plant available water (PAW), i.e. PAW 81 = to 81 mm plant available moisture measured at field capacity for the site. The two higher PAW sites (PAW 108 and PAW 81) were planted to the clonal hybrid, *E. gxn,* in 2012 whilst drier sites (PAW 36 and PAW 47) were planted in 2011 to the drought tolerant, *E. dunnii*.

The calculation of water deficit values is invaluable as opposed to the sole reliance on MAP when determining site-species matching or projecting timber growth and yields. Forest production in regions with a water deficit of greater than 400 mm and a dry season longer than 6 months are regarded as uneconomical for commercial forestry ventures due to low site productivity (MAI), poor wood properties (high lignin and resin contents) and high silviculture, and fire protection costs(Gonçalves *et al.*, 2017). To illustrate this, (Table 4.14) rainfall in 2011 was within the long-term MAP range for the Midlands region; however, water deficit calculations (WD) were particularly low, ranging from 7 – 18 mm, primary due to good rainfall during winter, combined with a well-distributed summer rainfall. During 2012, MAP equalled 920 mm but WD increased to 83 mm (PAW 108) - 131 mm (PAW 36) due to a dry winter. In 2015, MAP = 589 mm, accompanied by a long dry winter. Under such environmental conditions, WD ranged from 158 - 218 mm. Hence, records clearly support literature that MAP without cognisance of rainfall distribution and elevated mean annual temperatures (MAT) cannot fully explain environmental stressors leading to drought-induced damage and decreased MAI.

Table 4. 14: Mean annual precipitation (MAP) and water deficits for Hilton, KZN, South Africa. Climate data (2010 – 2019) for Cedara Research Centre (Source ARC – Pretoria). Water deficit methodology based on Thornthwaite (1948); Pereira *et al.* (2007).

Year	MAP (mm)	D01b (PAW 108): Water deficit (mm y^{-1})	F026 (PAW 81): Water deficit (mm y^{-1})	E013 (PAW 47): Water deficit (mm y^{-1})	D010 (PAW 36): Water deficit (mm y^{-1})	Mean water deficit by year (mm y^{-1})	Remarks
2010	848	107	124	152	162	**136**	
2011	**878**	**7**	**10**	**15**	**18**	**13**	Good rainfall in winter and even distribution
2012	**920**	**83**	**97**	**121**	**131**	**108**	Highest MAP but dry winter
2013	871	43	52	71	79	**61**	
2014	856	111	128	157	168	**141**	
2015	**589**	**158**	**177**	**208**	**218**	**190**	Low MAP and dry winter
2016	756	90	84	100	112	**97**	
2017	923	79	93	120	131	**106**	High MAP but dry winter
2018	918	26	33	48	56	**41**	
2019	683	139	159	193	208	**175**	Low MAP and dry winter
Mean WD by trial (mm y^{-1})	**824**	**84**	**96**	**119**	**128**		

Table 4.15 is a comparison of a Brazilian review of water deficit standards (Gonçalves *et al*., 2017) combined with results from this study, defined for *E. dunnii* and *E. gxn*. Water deficits recorded for the study sites, although moderate by South African standards, were still higher than the equivalent Brazilian Köppen Geiger climate type. However, edapho-climatic conditions are still quite different and should not be used to predict MAI, especially in terms of the greater rainfall across most Brazilian forestry sites. Hilton water deficits results were moderate by Brazilian and South Africa standards.

Table 4.15: Climate type, mean annual rainfall, temperature, actual evapotranspiration, length of dry season, recommended species, and expected average productivity. Based on trial results, Hilton – KZN, and Brazilian study (Gonçalves *et al*., 2017)

				Dry season			
Climate type [a]	Mean annual rainfall (mm)	Mean annual temperature (°C)	Mean actual evaporation (mm y^{-1})	Number of months	Mean Water deficit [b] (mm y^{-1})	Species/Hybrid [c]	Mean annual increment ($m^3 ha^{-1} y^{-1}$)
Cfa, Cfb - Brazil	1500 - 2500	13 - 20	500 - 1000	0 -2	0 - 250	EGU, Egr, Eur, Esa, Cci, Edu, Ebe, EUG	35 - 60
Cfb -Hilton, South Africa	900 - 1100	12 -21	950 - 1150	4 - 6	118-128	E.dunnii	22 - 23
Cfb -Hilton, South Africa	900 - 1100	12 -21	950 - 1150	4 - 6	84-96	EGN	21 - 26

[a] Climate type according to Köppen climatic classification (Gonçalves *et al*., 2017 – modified)
[b] Soil water balance based on Thornthwaite (1948)
[c] Egr = *Eucalyptus grandis*, Esa = *E. saligna*, Eur = *E. urophylla*, Cci = *Corymbia citriodora*, Ebe = *E. benthamii*, Edu = *E. dunnii*, EGU = *E. urophylla* × *E. grandis*, EUG = *E. urophylla* × E. *globulus, EGN- E. grandis x E. nitens.*

4.1.1. Mean water deficits (WD)

Water deficits (WD) for the four trial sites were moderate compared to cited literature (Gonçalves *et al*., 2017); however, temperatures were also commensurately lower than citations (Table 4.15) thus resulting in lower productivity. It is important to note that different eucalypt species and hybrids were tested so a direct comparison of MAI across sites was not possible. Winter temperatures in Hilton can decline to 0 °C, thus no productive photosynthesis occurred for that day with a loss in biomass productivity.

Mean annual water deficits (WD) (Figure 4.1; Table 4.16) ranged from 84 mm y^{-1} (s.e = 14 mm y^{-1}) for site D01b (PAW 108) to 114 mm y^{-1} (s.e = 20 mm y^{-1}) for site D010 (PAW 36). Ranges for site D01b WD (planted 2012) were 26 - 158 mm y^{-1} whilst site D010 (planted 2011) recorded a range from 18 – 218 mm y^{-1} (Table 4.16). Both water deficit ranges (high to low PAW sites) were higher than a comparative Brazilian Cfb site (WD = 0 - 250 mm y^{-1}) (Table 4.15).

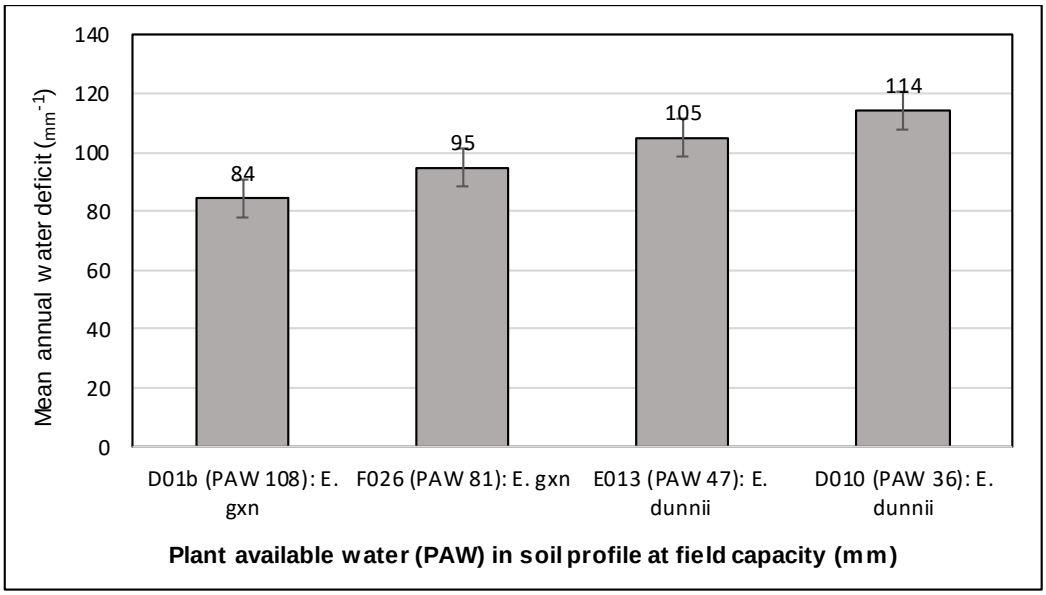

Figure 4.1: Total plant available water (PAW) in the soil profile at field capacity (mm). Four field trials, Hilton, KZN, South Africa. Based on Thornthwaite (1948)

Table 4.16: Summary statistics for trial water deficits (WD), Hilton KZN (2011 – 2018)

	D01b (PAW 108)	F026 (PAW 81)	E013 (PAW 47)	D010 (PAW 36)
Species/hybrid	*E. gxn*	*E. gxn*	*E. dunnii*	*E. dunnii*
Mean WD full rotation (mm y^{-1})	84	95	105	114
Standard deviation	43.4	47.7	61.3	63.4
Standard error	13.7	15.1	19.4	20.0
Range	132	144	193	200
Min	26	33	15	18
Max	158	177	208	218

4.1.2. Comparing water deficits (WD) and tree growth trends

Gonçalves *et al*. (2017) collated MAI data from a range of climatic sites planted to the main commercial *Eucalyptus* species. MAP ranged from 850 -1600 mm, MAT = 18 – 28 °C and WD 0 – 250 mm y^{-1}, with the number of months recording water deficits from 0 – 6 months (Figure 4.2). A strong correlation ($r = 0.86$, $p < 0.001$) was observed between MAI and water deficit (WD) with the highest average MAI = 50 m^3 ha^{-1} y^{-1} where no water deficit existed. A 10 mm increase in WD resulted in 1 m^3 ha^{-1} y^{-1} decrease in MAI.

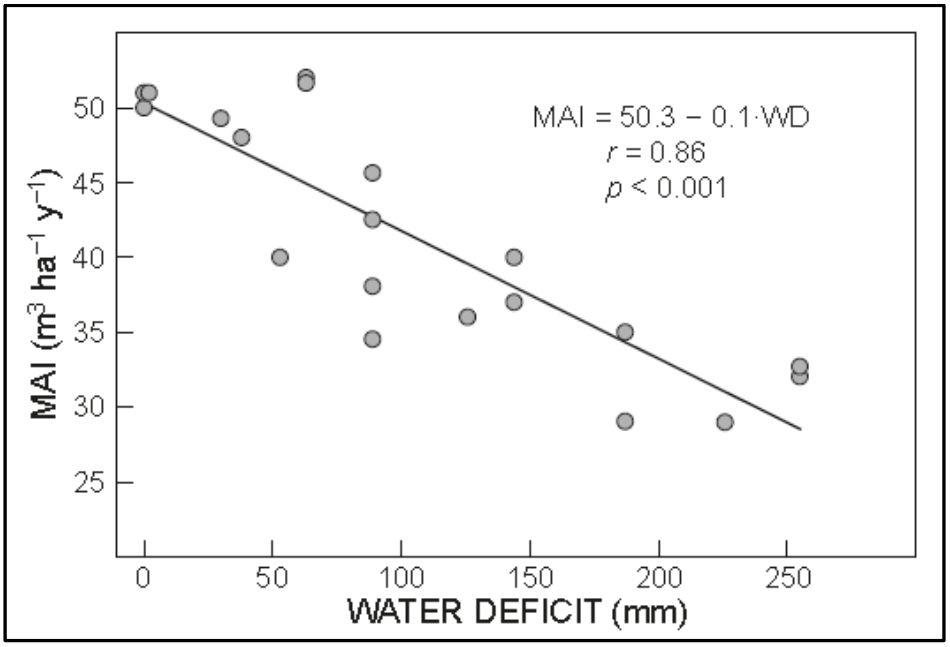

Figure 4.2: Relationship between mean annual increment (MAI) and water deficit for the main commercial eucalypts in Brazil across 20 data points (reproduced from Gonçalves *et al*., 2017)

With reference to the above study (Gonçalves *et al*., 2017) (Figure 4.3), an attempt was made to plot water deficit (WD) against measures of stand productivity (height, Dbh increment, basal area increment and MAI) across the four field trials. It was necessary to use the growth rates for all these variables as trial measurement dates did not exactly coincide and final age measurements varied from age 87 to 99 months. Fewer data points existed (4 for this study vs. 20 for Brazilian study) and thus simple correlations were calculated to identify approximate trends and should not be regarded as definitive (Figure 4.3). Water deficit (mm y^{-1}) plotted against Dbh increment, basal area increment or MAI, suffered from the fact that stocking levels amongst trials did vary (particularly Trial F026) and hence were not an accurate reflection of the potential volume of basal area growth. The relationship between water deficit and height growth rate produced a strongly linear, negative correlation (r = 0.92) for the four trial sites (Figure 4.3) and reinforced the value of a site index (SI) based on dominant heights.

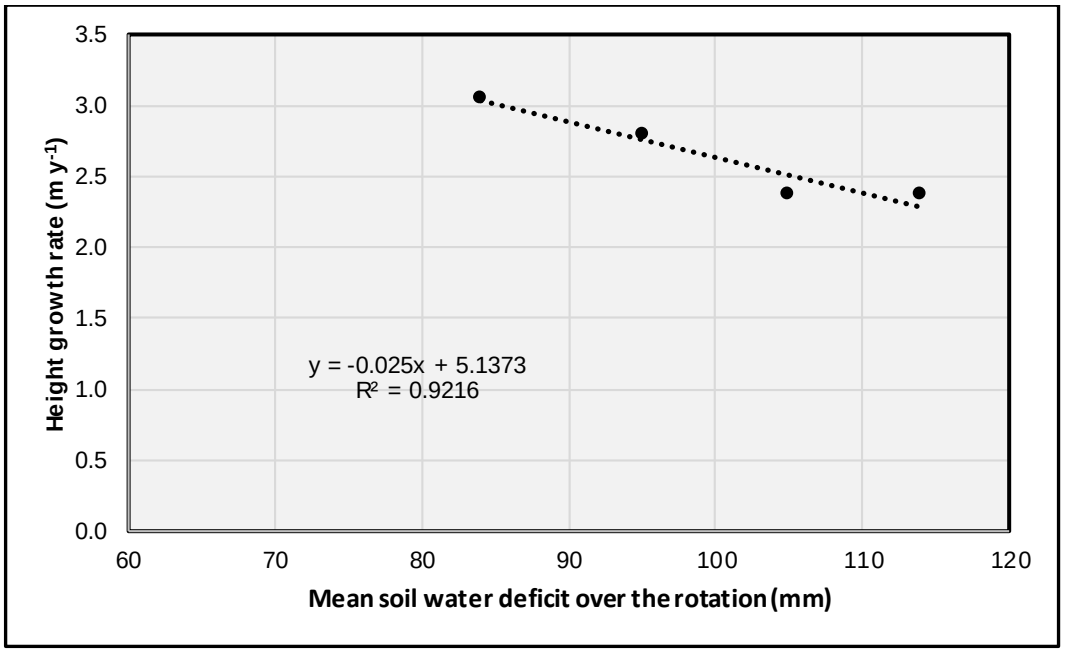

Figure 4.3 Stand height growth rate trends as a function of average water deficit calculated over the rotation

As only two pairs of data were available, it was only possible to illustrate a trend line per species, with *E. dunnii* only slightly affected by a 10 mm increase in water deficit, whilst *E. gxn* was more sensitive to a similar increase (Figure 4.4).

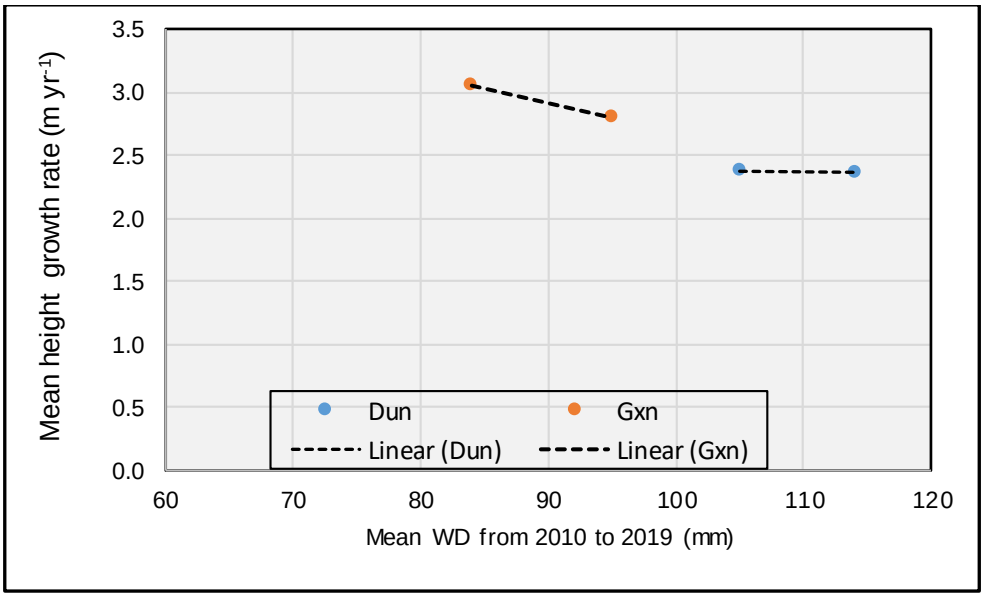

Figure 4.4 Stand height growth rate as a function of average water deficit calculated over the rotation by genotype. Dun = *E. dunnii* seedling. Gxn = *E. gxn* clone

4.2. TRIAL STOCKING COMPARISON

In order to better interrogate responses of stocking to site quality (fertility) and water deficit, a plot (Figure 4.5) comparing stocking over full rotation was plotted for all four trials against the water deficit for the same periods. This became increasingly apparent as three of the four trials all followed similar low mortality rates (mean = 1533 Spha across three trials) through to full rotation, with one trial, F026, revealing a much lower stocking of 1256 Spha. Water deficits across trial sites reached a peak by 48 months (Figure 4.5) of 200 mm y^{-1} but thereafter decreased to under 50 mm y^{-1} by full rotation. Conditions were very favourable for maximum above ground biomass partitioning, possibly excessively so under a high stocking level towards full rotation and hence the advent of increased mortality.

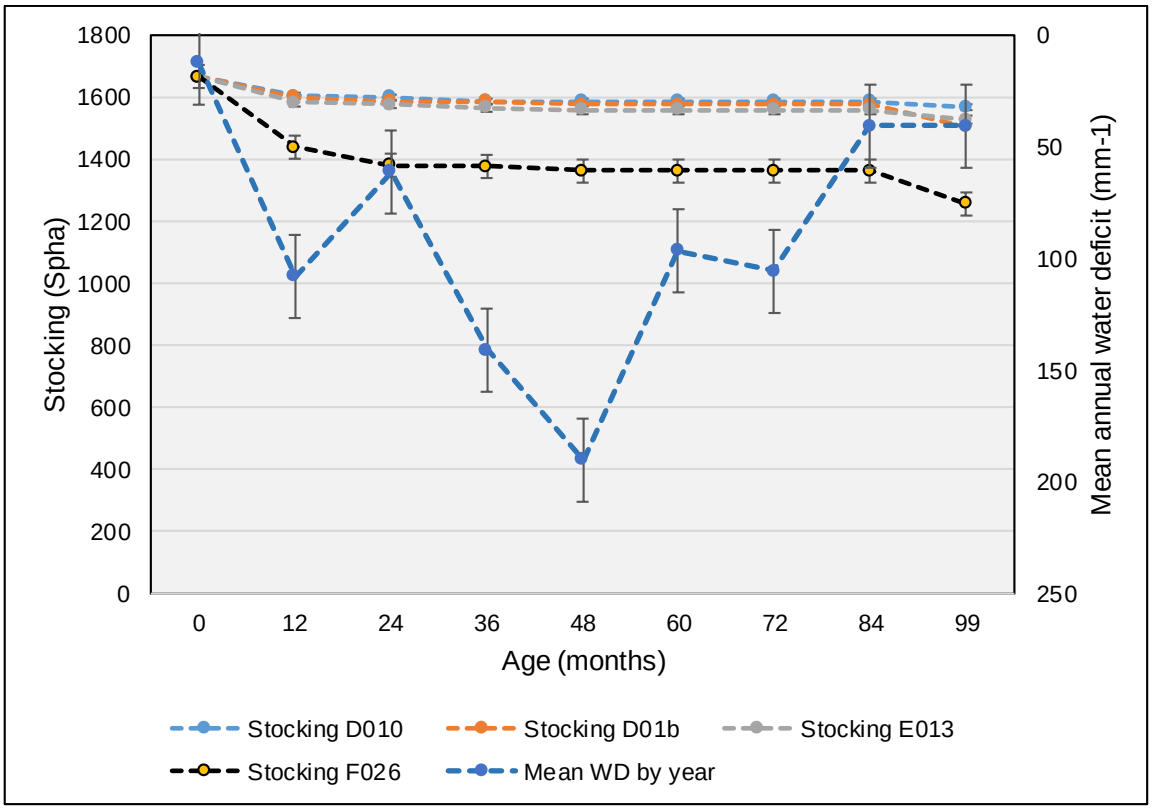

Figure 4.5: Stocking and PAW over 4 trials up to clearfell. Hilton, KZN, South Africa. Water deficit, based on Thornthwaite (1948) and Pereira *et al*. (2007), is the average value across all 4 experimental sites to illustrate year-on-year fluctuations

Results show that stocking showed an initial gradual decrease across three of the four trial sites, as is experienced under most operational planting conditions. However, mortality at Site F026, *E. gxn*, was much higher, decreasing to 1439 Spha by 12 months. Reasons for such mortality were not biotic although the potential for the 'ball and socket' syndrome could not be ruled out but roots were not excavated to confirm. Factors such as plant quality and silviculture inputs were exactly as for Trial D01b. It was quite clear that stocking was under

pressure during the final year, probably as severe intraspecific competition set in. To explain this more precisely, the size density relationship was considered whereby trees of bigger size compete more intensely and maximum stocking of a site is therefore strongly dependent on tree size. As trees grow in size, they edge closer to the maximum size-density relationship line (a zone of imminent mortality). To support this assumption, the relative stand density was applied (Curtis, 2012). This definition states that relative stand density equates to the basal area divided by the quadratic mean diameter (Table 4.17):

Relative density (RD) = Basal area / (sqrt (Dq)) (Curtis, 2012)

Table 4.17 Summary statistics for PAW and RD values (WD), Hilton KZN (2011 - 2018)

Trial Site	Species	PAW (mm)	Dbh	BA (m^2 ha^{-1})	RD
D01b	*E. gxn*	108	14.3	25.6	6.8
F026	*E. gxn*	81	14.5	21.0	5.5
E013	*E. dunnii*	47	13.8	24.3	6.5
D010	*E. dunnii*	36	14.2	25.9	6.9

The RD for eucalypts is considered as slightly less tolerant than pines and hence a lower initial stocking level should be applied to silviculture standards (Table 4.18). In 'fully stocked' zone there is usually moderate levels of mortality already, i.e. weaker trees start to die and by the time a compartment reaches an RD = 12, it is in a poor state with multiple dead standing trees and excessive windfalls. At such a relative density, every tree is in danger of dying and not just supressed or weak individuals.

Table 4.18: Relative stand density level values and description (Curtis, 2012)

Relative density level	Comment
< 1.5	Excessively open and exposed
1.5 - 3.0	Free growing
3.0 – 6.0	Zone of increasing competition
6.0 – 12.0	Fully stocked
> 12.0	Zone of imminent mortality

In terms of the experiment series, most sites were in the fully stocked zone by age 99 months, possibly sooner, i.e. they had exceeded the RD value of 6 by that age. Under such circumstances, tree mortality had set in, characterised on site F026 by multiple and scattered windfalls in comparison to the other trials, even where site conditions in terms of WD and soil fertility were comparably good. It is also worth considering that the RD value

for clonal *E. gxn*, when windfall and mortality may set in, could be lower than 12 due to the adventitious rooting system. Such hybrids tend to colonise at a shallower depth with root growth more limited to the top 40 cm (Hoffmann *et al*., 1978) of soil making them potentially more susceptible to toppling or a decrease in WD over consecutive years. The reason for the mortality dip at rotation end could therefore not attributed to an increased water deficit (Figure 4.6) but more likely an increase in stand relative density. If this assumption is correct, it may also explain why the high WD by mid rotation did not kill the trees. Simplistically stated, trees were not under severe intraspecific competition at this stage. Alternatively it is also possible that the water deficit was never low enough to kill trees outright and mortality at rotation end was due to non-water related causes.

4.3. DBH AND BASAL AREA DIFFERENCES - MAIN AND INTERACTIVE EFFECTS FROM PLANTING TO FULL ROTATION

HIGH PRODUCTIVITY SITE (D010)

Means squares values were used to account for variance in main effects and interactions (Days 0 - 3011) for Gld and BA, and are represented (Figure 4.6, Figure 4.7). Main effects included rep, residue management, root plug volume (RPV), nursery hardening and application or no application of insecticide, accounted for 96% of differences at Day 0 (14 days after planting). RPV accounted for 85% of differences in Gld. Main effects swiftly decreased in terms of percentage of variance accounted for over time, decreasing to 56% by Day 3011.

Root plug size accounted for 85% of variance within Gld up to 3 months and decreased to below 5% for the duration of the trial (Figure 4.6). This emphasized the impact of nursery conditioning on early survival especially considering Gld as a major driver of uniformity and survival, but RPV decreased to only 4.5% by Day 394. The impact of replication (rep) grew in strength after a year (10.5%), accounting for 52% by Day 3011. The blocking of reps did account for any site gradient on the basis of the assumption that there is uniformity within reps, although differences between reps is desirable. Accounting for Gld variance could be explained by plug size up to three months and thereafter other main effects or interactions became more important.

The trial site was relatively even in terms of slope and replications were positioned such that each of four replications were equally oriented to slope and potential moisture gradients. However, even where three of the four reps were uniform in terms of site, differences in one rep would still be sufficient to explain a large portion of the variance.

Aspect (100% of trial = W), slope and soil type were uniform (88% of trial = Magwa 1100) with 89% of effective rooting depth extending to 50 cm. The moisture gradient could also not explain the significant impact of rep. Most plant available water (PAW) was in the region of 32 – 37 mm m^{-1}, with isolated pockets at 79 mm m^{-1}. None of these main effects could further account for Gld, although hardening did explain 9% of variance at Day 0, but this shrunk to 0.4% by end of rotation (Day 3011).

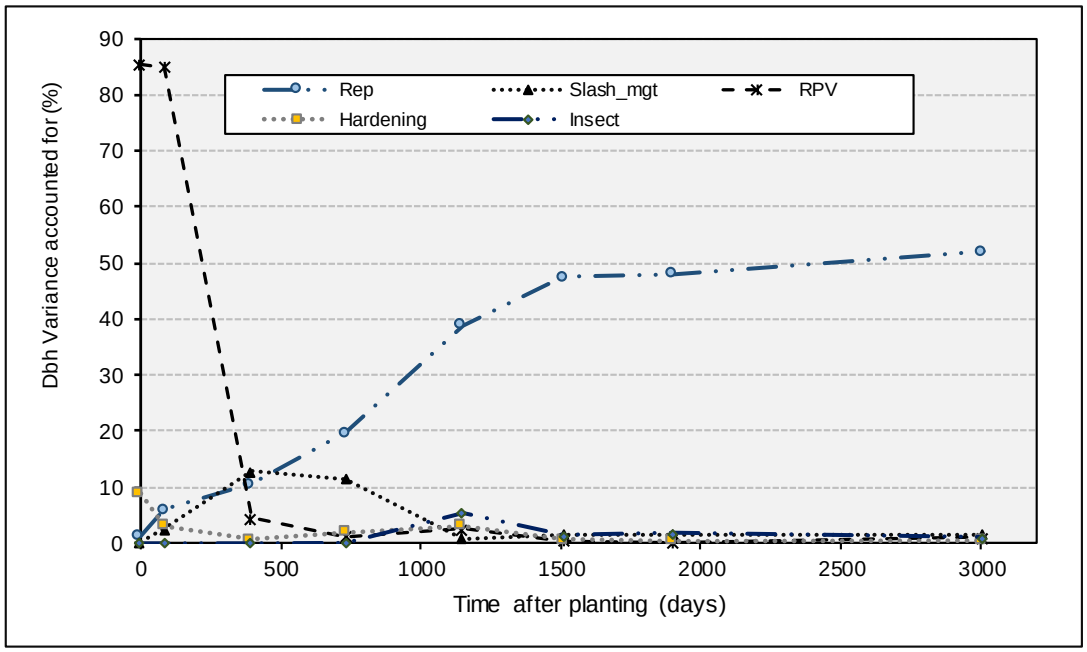

Figure 4.6: Trial D010, variance accounted for in Gld/Dbh - Main effects

Although rep (main effect) was the dominant factor to account for variance in Dbh over the full rotation of the trial, treatment interactions would account for more than 10% of variance at different ages. At 1 - 2 years, (394 – 734 DAP) the interaction between residue management (slash_mgt) and plug size (RPV) accounted for 23% of variance within Dbh, but decreased to 17% the following year. This interaction (Slash_mgt x RPV) progressively decreased in accounting for Dbh variance to only 8% by rotation end. As the impact of residue management x plug size decreased, the interaction between residue management and hardening (Slash_mgt x Hardening) peaked at 11%; however, the mean squares (MS) variation quickly decreased thereafter (<1%) and played no further role. The interaction of root plug volume and nursery hardening (RPV x Hardening) was important in terms of explaining variance in Dbh, from three years onwards (Figure 4.7), but could only explain 15% of the variance and the importance of the factors so late into the trial rotation was surprising. It was postulated that such an interaction would explain much more variability in Dbh on marginal sites.

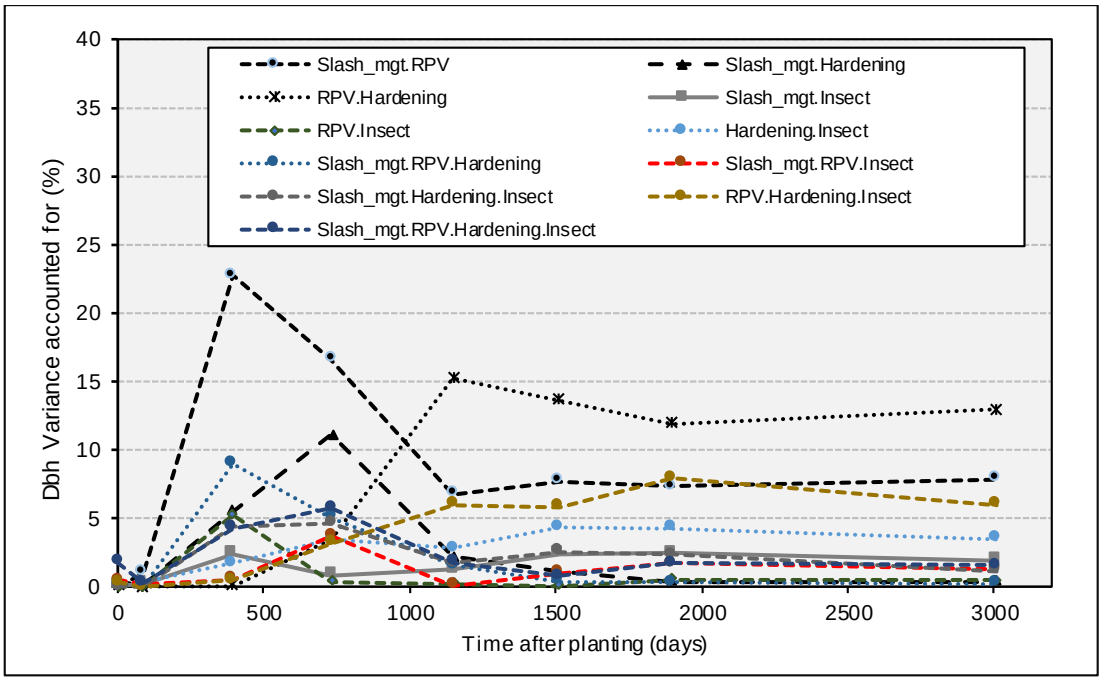

Figure 4.7: Trial D010, variance accounted for in Gld/Dbh - Interactions

Erdle (2019) states that basal area (m^2 ha^{-1}) closely relates to volume, is simple to calculate, is a useful measure of site occupancy and can be successfully utilised to predict future stand development. In terms of main effects, rep played a greater role in explaining variance within BA after two years (734 days), increasing until it explained 55% of variance at rotation end (Day 3011). Residue management (slash_mgt) explained nearly double the variance in BA (21 - 22%), as opposed to Dbh, between 1 and 2 years, but this did not reflect at final rotation, explaining only 1% of variance within BA at trial termination (Figure 4.8). Plug size (RPV) explained 87% of variance within BA for the first three months but thereafter mean square values were of little consequence.

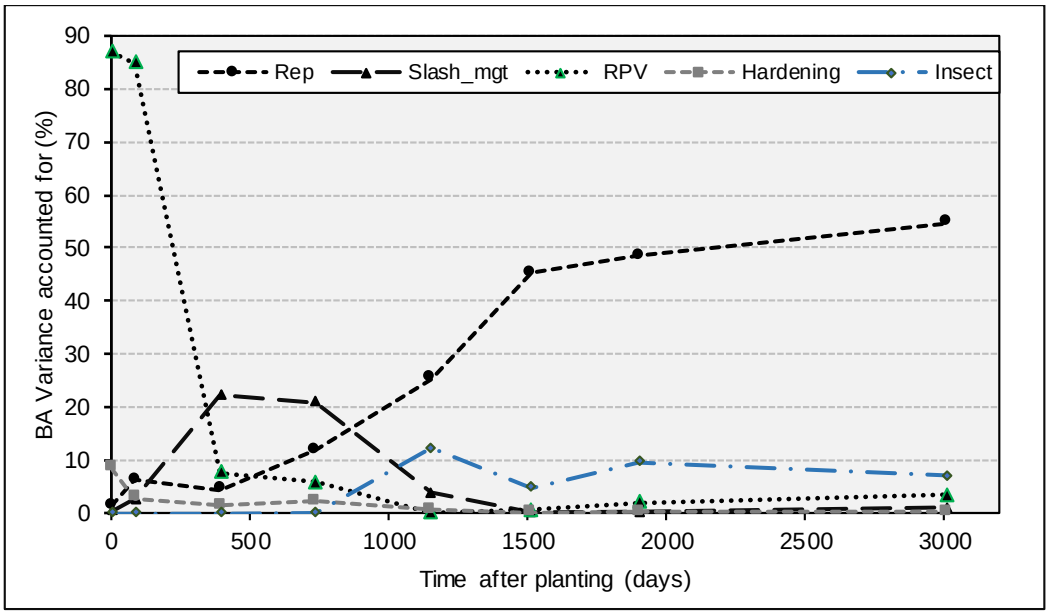

Figure 4.8: Trial D010, variance accounted for in basal area (BA) – Main effects

In terms of treatment interactions only those where MS values exceeded 10% are reported hereunder. The same treatment interactions were expected to account for variance within BA as for Dbh. This proved to be correct with only residue management x plug size (Slash_mgt x RPV) interaction accounting for 16 - 19% of BA between 1 and 2 years of age but decreasing to <8% by rotation end. No other treatment interactions could explain BA variance (Figure 4.9).

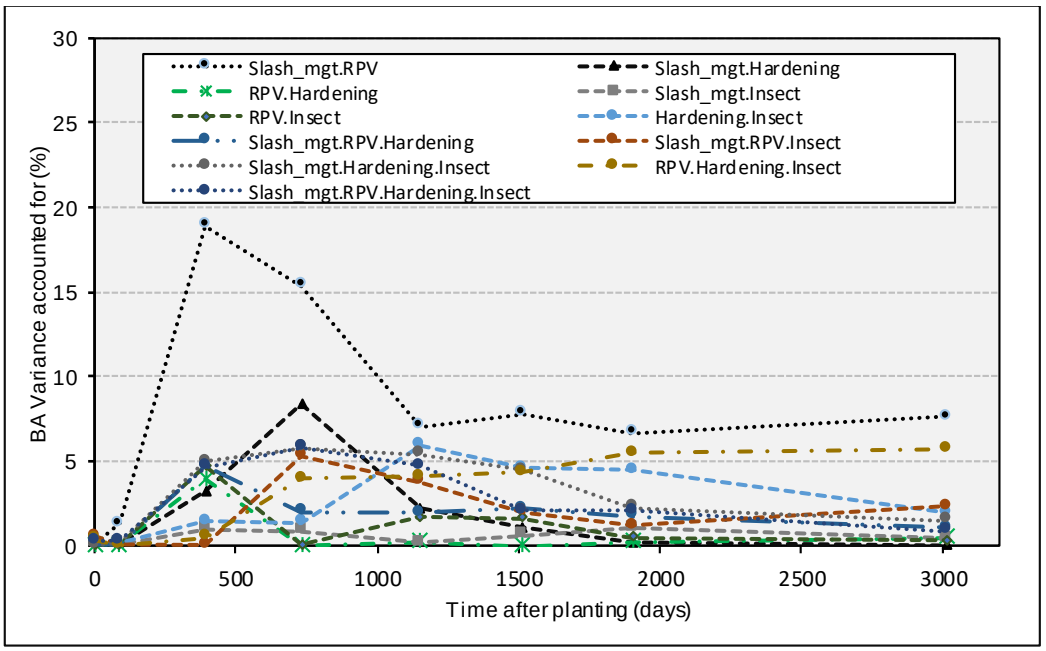

Figure 4.9: Trial D010, variance accounted for in basal area (BA as $m^2 ha^{-1}$) – Interactions

4.4. DBH AND BASAL AREA DIFFERENCES - MAIN AND INTERACTIVE EFFECTS FROM PLANTING TO FULL ROTATION

MEDIUM PRODUCTIVITY SITE (E013)

Means squares values were used to account for variance in Gld and BA caused by the main effects and interactions (Days 0 - 2985) (Figure 4.10; Figure 4.11). Main effects, rep, residue management, root plug volume (RPV), nursery hardening and insecticide treatment accounted for 91% of differences at Day 0 (14 days after planting), with RPV accounting for 89% of differences in Gld. Main effects of RPV declined to 19% of variance by Day 378 and 16% by Day 724 (≈2 years) after planting. Instead of linearly declining, RPV increased in terms of variance, accounting for 23% at day 1505 (≈4 years) before declining to 14% at full rotation. Mean square variation for RPV did not necessarily pinpoint which root plug volume performed better (105 cm^3 vs 60 cm^3) but indicated that it played a significant role in accounting for variation of Gld/Dbh.

The impact of rep was low and only explained 16% at day 724 (2 yeas), increasing to a maximum of 25% by Day 2985 (8 years). The effect of rep on Gld/Dbh variation was attributed to site effect; however, 82% of the trial was a single soil form, Magwa 1100, with 86% of effective rooting depth extending to 50 cm soil depth and a further 14% to 90 cm. Aspect for the trial was westerly. It was hypothesized that slope was primarily responsible for a moisture gradient as 52% of the site was planted on a slope class of 0 - 15% (replication 3 and 4) whilst 48% was on a steeper slope of 16 - 20% (rep 1 and 2).

Residue management (slash_mgt) in accounted for 58% of Dbh variance at day 378 (≈ 1 year), declining to 49% by Day 724 (≈ 2 year). Thereafter, residue management accounted for 14% of variance in Dbh by rotation end (Day 2985). Initial Gld growth was driven by plug size (RPV) and nursery conditioning, but would be superseded as canopy closure approached and demands on site increased. Growth variability in response to residue management revealed an initial increase in Dbh on the burn treatment. With time, all three residue treatments became less influential in driving Dbh variance.

Root plug volume rapidly declined (Figure 4.10) in accounting for variation in Dbh at 1 year, whilst residue management significantly increased over the next two years and accounted for up to 49% of Dbh variation by the second year. Thereafter, residue management declined in influence in accounting for Dbh variability and RPV again increased until both accounted for 14% of Dbh variance at full rotation. In summary as RPV increased in accounting for Dbh variation, residue management declined until a form of stasis existed at

rotation end. None of the silviculture treatment interactions, i.e. residue, plug size (RPV), nursery hardening or insect application accounted for more than 10% of variation in Dbh at any time and main effects would account for the significantly largest share of variability.

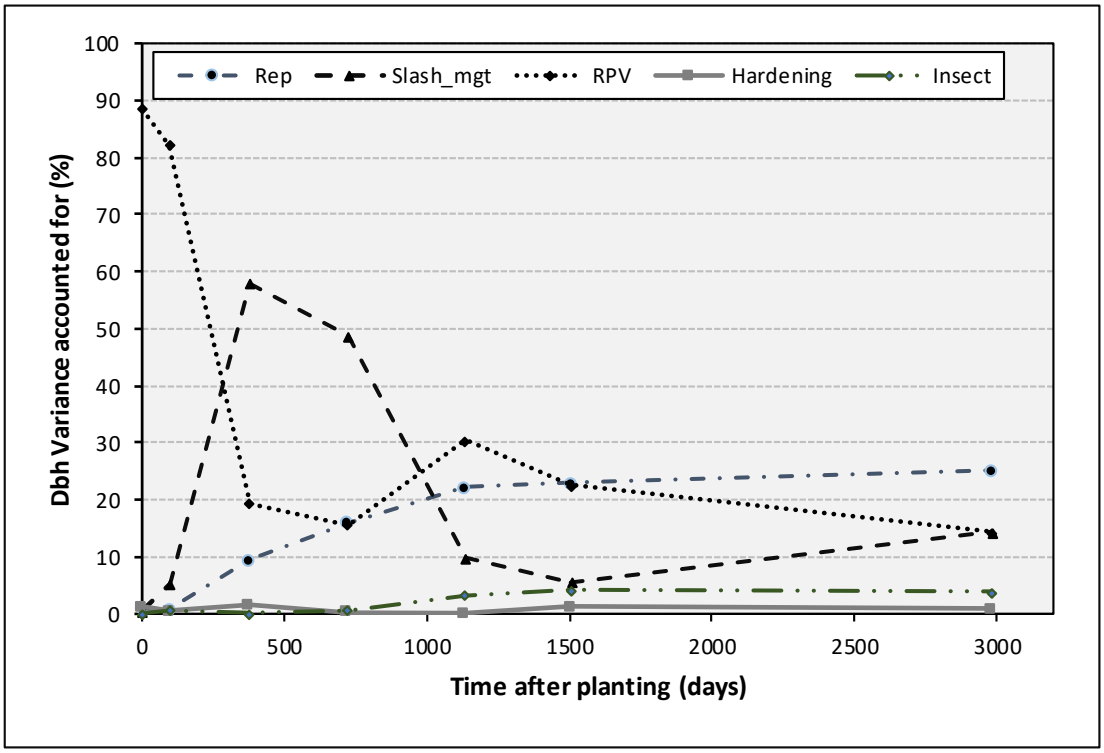

Figure 4.10: Trial E013, variance accounted for in Gld/Dbh - Main effects

Main effects accounted for 90% of variance (Trial site E013) in BA with rep playing a lesser role and peaking at 32% at Day 1505 (≈ 4 years), before declining to 15% at full rotation (Figure 4.11). Residue management (slash_mgt) accounted for 55% of BA variance at Day 378 (≈ 1 year) but declined to 17% by three years and nearly no effect at full rotation. Root plug volume (RPV) explained over 80% of BA variance for the first 3 months but rapidly declined to 23% at 3 years and 11% at full rotation (Day 2985). As opposed to Trial D010, Trial E013 showed two interactions, 1) Residue management x Hardening and 2) RPV x Hardening, accounting for 14% and 13% BA variance respectively (Figure 4.12). ANOVA tests consistently reflected the importance of hardening of planting stock in the nursery up to full rotation. The importance of this factor was unforeseen and initially regarded as subordinate to other silviculture treatments.

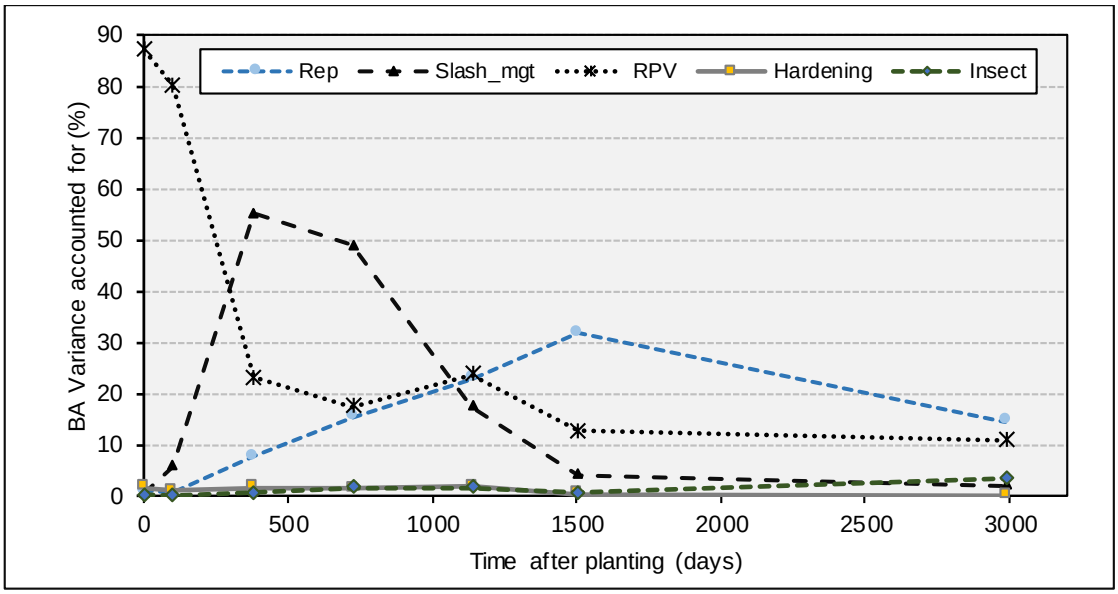

Figure 4.11: Trial E013, variance accounted for in basal area – Main effects

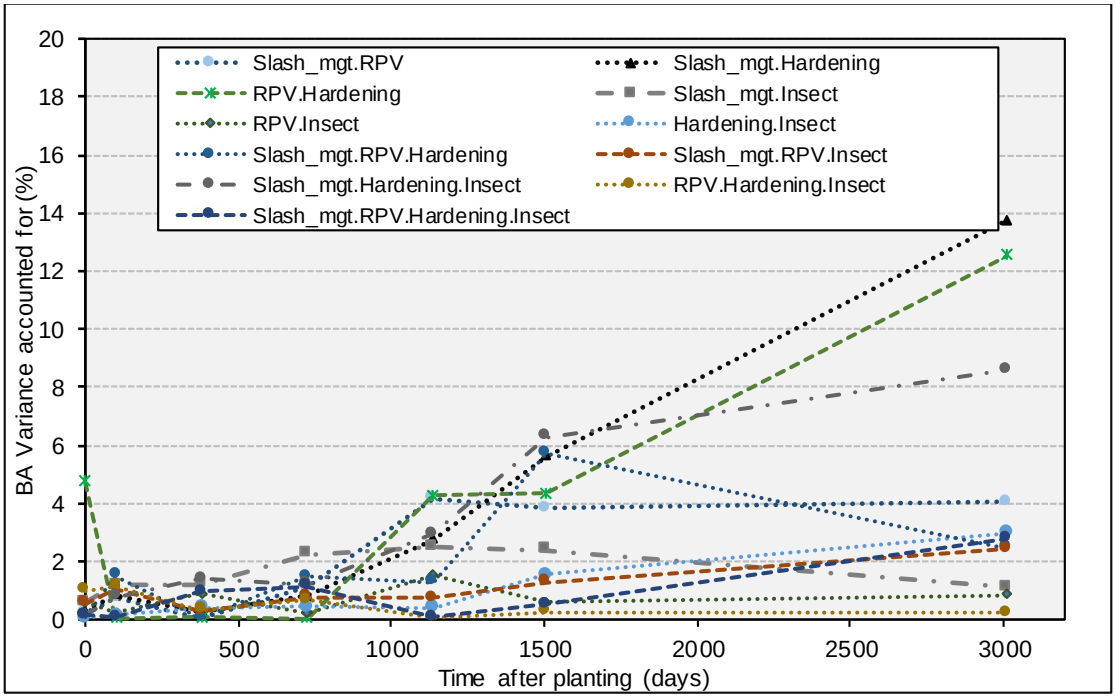

Figure 4.12: Trial E013, variance accounted for in basal area – interactions

4.5. DBH AND BASAL AREA DIFFERENCES - MAIN AND INTERACTIVE EFFECTS FROM PLANTING TO FULL ROTATION

MEDIUM PRODUCTIVITY SITE (F026)

Means squares values were used to account for variance in Gld and BA caused by the main effects and interactions (Days 0 - 2585) (Figure 4.13, Figure 4.14). Main effects included rep, slash management, root plug volume (RPV), nursery and application of insecticide treatment. Main effects accounted for 50% of Dbh variance at Day 0 (14 days after planting),

decreasing to 41% by Day 2585 (≈7 years). Rep accounted for 18% of Gld variation (Day 0) and only reappeared 3 years later, accounting for 21% of Dbh variance. Rep accounted for 24% of variation in Dbh at full rotation (7 years). Apedal soils, Inanda 1100 (43% of site) and Kranskop 1100 (57%) were the main soil forms. Aspect was split between 44% of the trial on the easterly side whilst 56% was northerly. The whole trial fell into the 0 -15% slope. Soil depth for the trial site was between 50 – 90 cm and with PAW ranging from 71 – 95 mm m^{-1}.

Residue management (slash_mgt) was responsible for 27% of Gld variance at 6 months and retained this percentage for the next 2 years. By full rotation, residue management only accounted for 10% of Dbh variation. RPV accounted for 24% of Gld variation at planting. This doubled in 6 months to 49%, before progressively decreasing to 36% at 18 months. At Day 2585, residue management only accounted for 10% of Dbh variance whilst rep had increased to 24% (Figure 4.13). The main effect, hardening, showed a delayed response but at 6 months was responsible for 13% of Gld variance, progressively decreasing to 8% at 2 years and rapidly declining to 1% at 7 years.

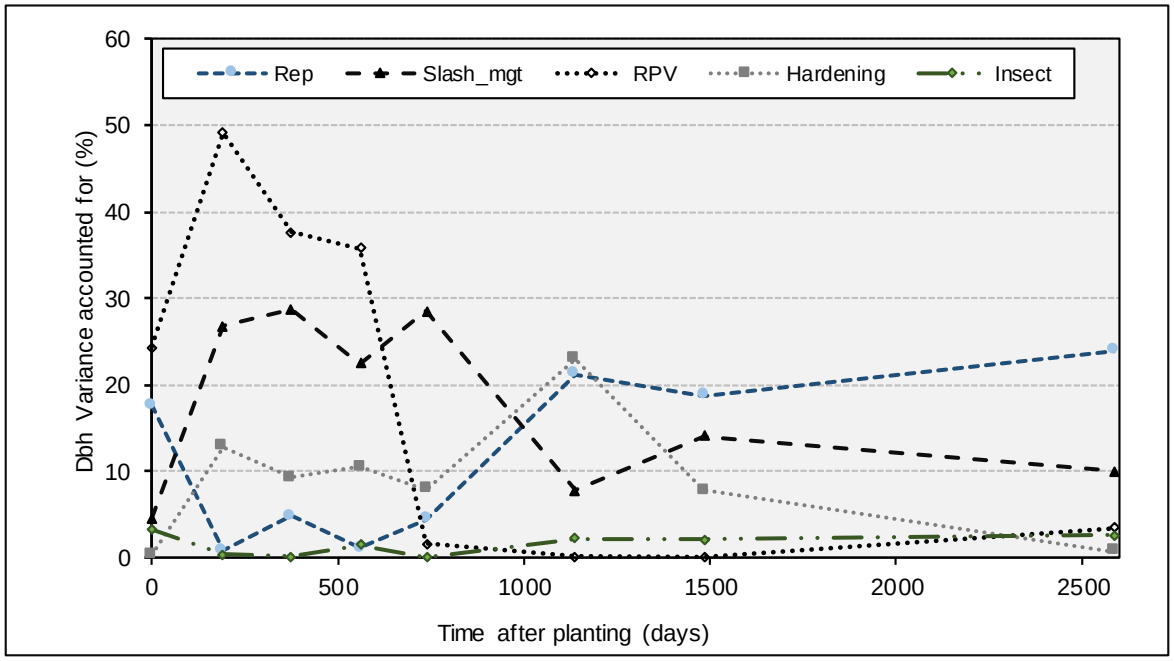

Figure 4.13: Trial F026, variance accounted for in Gld/Dbh - Main effects

Of the interactions, only two combinations accounted for over 10% of Dbh variance (Figure 4.14). Nursery hardening and insecticide treatment accounted for 11% of Dbh variance at 2 years and then disappeared. Root plug volume (RPV) x nursery hardening x insecticide application accounted for 13% of Dbh variance at rotation end.

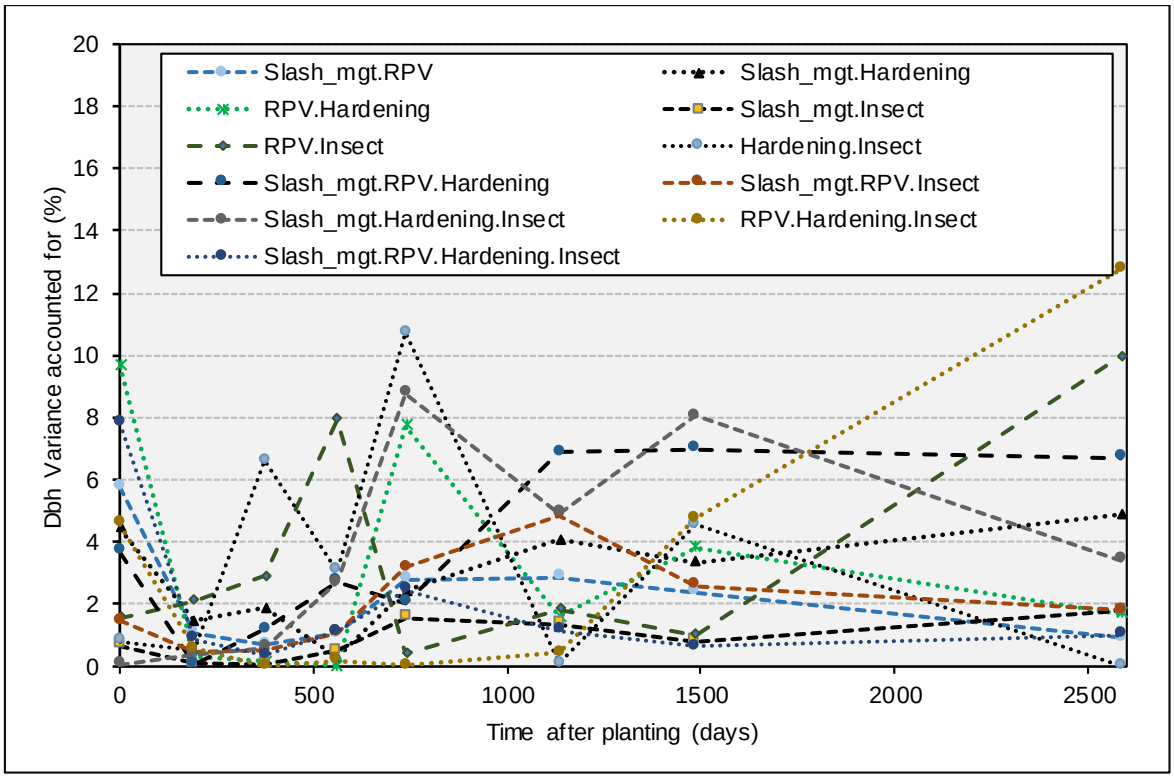

Figure 4.14: Trial F026, variance accounted for in Gld/Dbh – Interactions

Main effects accounted for 48% of basal area (BA) variance (Trial F026). From Day 374 (≈ 1 year) rep accounted for 15% of BA variance and nearly doubled (27%) at 2 years. Rep remained the greatest driver of main effects up to 4 years (32%) and decreased to 21% of BA rotation end. Residue management (slash_mgt) accounted for 35% of BA variance at Day 191 (≈ 6 months) gradually declining to 23% at 2 years before stabilising at 13% at full rotation (Figure 4.15).

Plug size accounted for 10% of BA variance at planting rapidly increasing to 41% at 3 months, but declining to 20% at 18 months. Thereafter RPV accounted for a relatively stable 10 – 13% of BA variance until full rotation at 7 years. Hardening of nursery stock would only exceed the minimum boundary of 10% of BA variance (12%) at 3 months, fluctuating to 9% by Day 2585 (≈7 years) (Figure 4.15). Trial F026 showed a single interaction of root plug volume x hardening xinsecticide (RPV X hardening xinsect) accounting for 16% of variance in BA from 18 months through to full rotation (Figure 4.16).

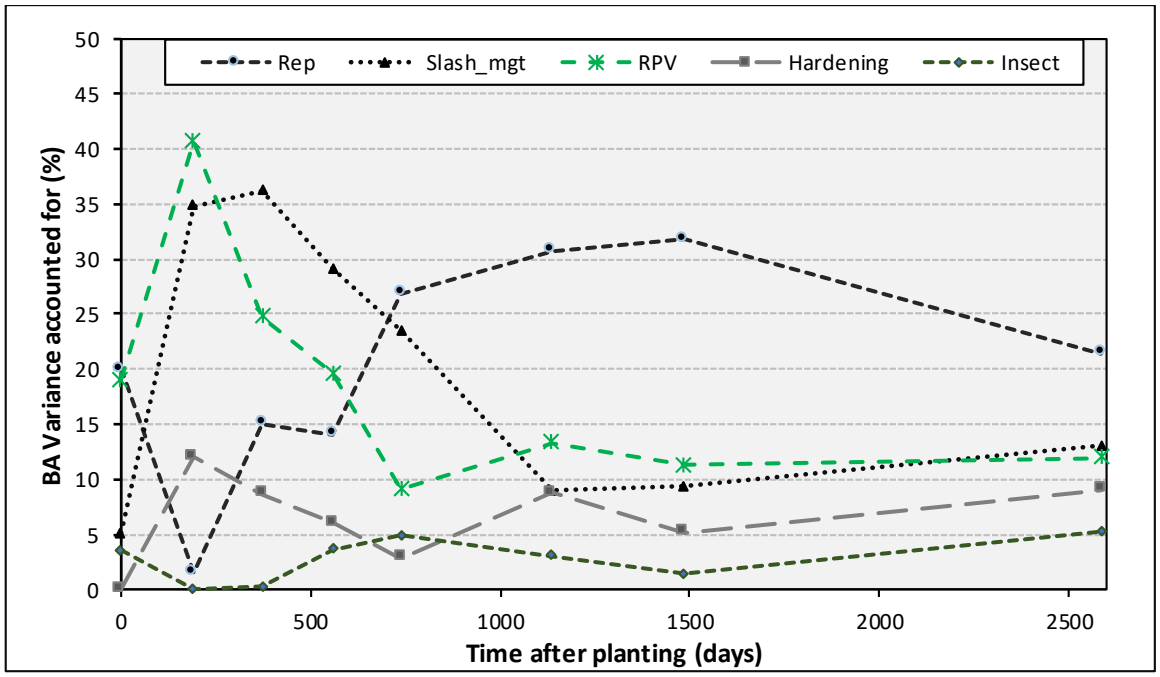

Figure 4.15: Trial F026, variance accounted for in basal area – Main effects

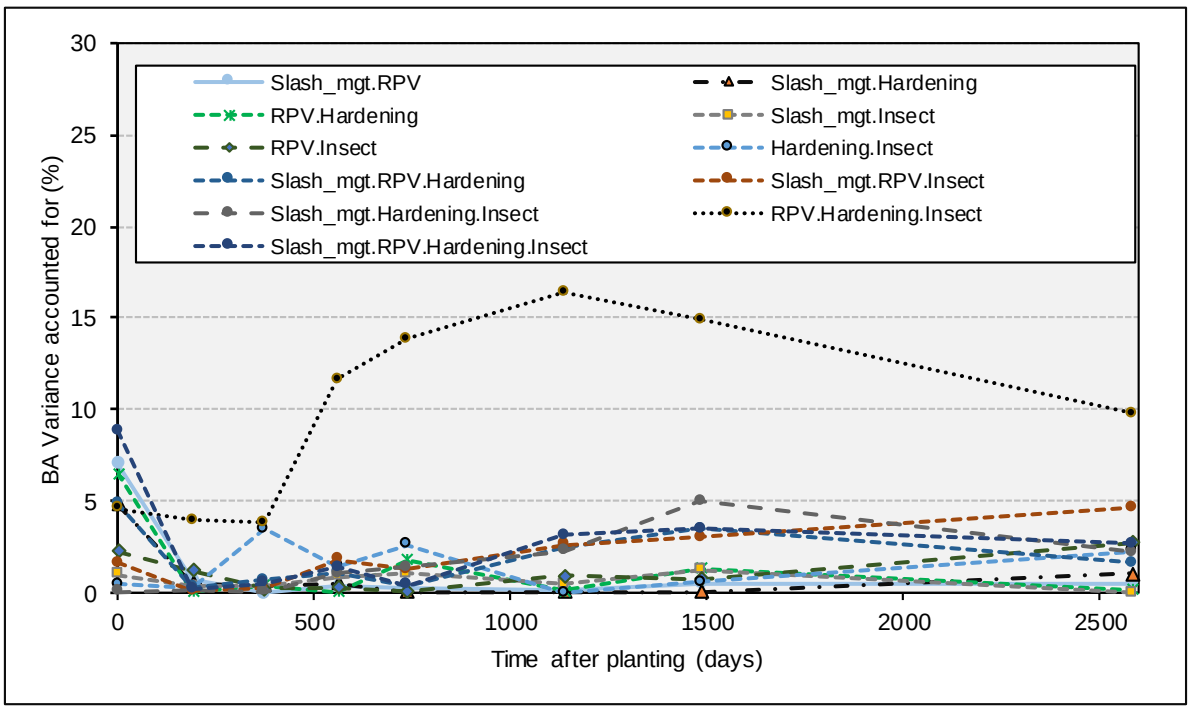

Figure 4.16: Trial F026, variance accounted for in basal area – interactions

4.6. DBH AND BASAL AREA DIFFERENCES - MAIN AND INTERACTIVE EFFECTS FROM PLANTING TO FULL ROTATION

HIGH PRODUCTIVITY SITE (D01B)

Main effects rep, slash management, plug size (RPV), hardening and insecticide treatment accounted for 31% of Gld variation 14 days after planting (Day 0), decreasing to 14% by

Day 2656 (≈7 years) (Figure 4.17). Rep was responsible for 15% of Gld variation at 6 months (Day 238). At 378 days, (≈1 year) rep was responsible for 22% of Dbh variation and 25% by the third year, declining to 9% at 7 years. Soil form was uniform with 100% of the site comprising Kranskop 1100, all positioned on a northerly aspect. Slope was more pronounced with 50% of the site in the 0 – 15% class and 50% in the 16 – 20% slope class. Soil depth was uniformly deep at 90 cm effective rooting depth whilst PAW was the best of all four-trial sites at 108 mm m^{-1}.

Residue management was responsible for 11% of Gld variance at 6 months (238 days). At 378 days (≈1 year) residue management accounted for nearly double (22%) this variability, but declined to a negligible effect (<2%) by full rotation. RPV (plug size) was of lesser significance in Trial D01b and never accounted for more than 1% of Dbh variance at full rotation (Figure 4.17). Nursery hardening was responsible for 37% of Gld variance at 3 months, decreasing to 13% at 1 year and never increasing to more than 2% at full rotation. Insecticide treatment would only account for Gld variation just after planting (11%) and declined to completely negligible levels by Day 2656.

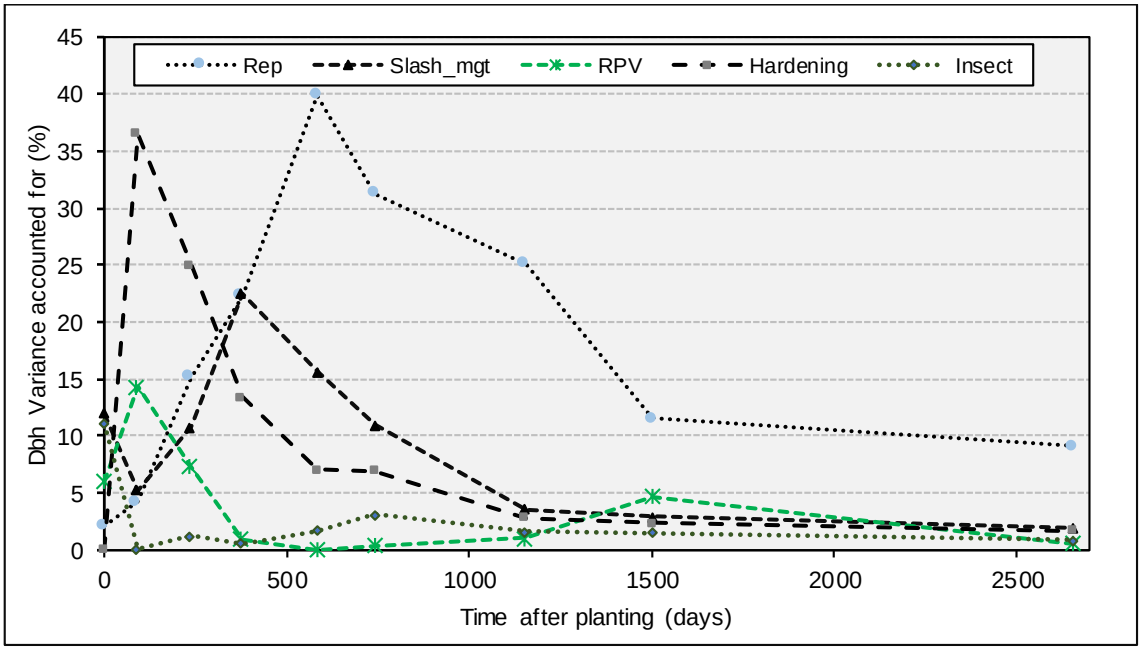

Figure 4.17: Trial D01b, variance accounted for in Gld/Dbh - Main effects

Treatment interactions in Trial D01b accounted for Dbh variance for the following treatment combinations; 1) Residue management (slash_mgt) x hardening, 2) Root plug volume x hardening and 3) RPV x insecticide (insect). Residue management combined with nursery hardening accounted for 11% of Dbh variance at 3 years and then rapidly declined, whilst a RPV x hardening combination appeared at 4 years and accounted for 27% of Dbh

variance at full rotation. A combination of RPV and insecticide treatment was responsible for 27% of Dbh variance at 7 years.

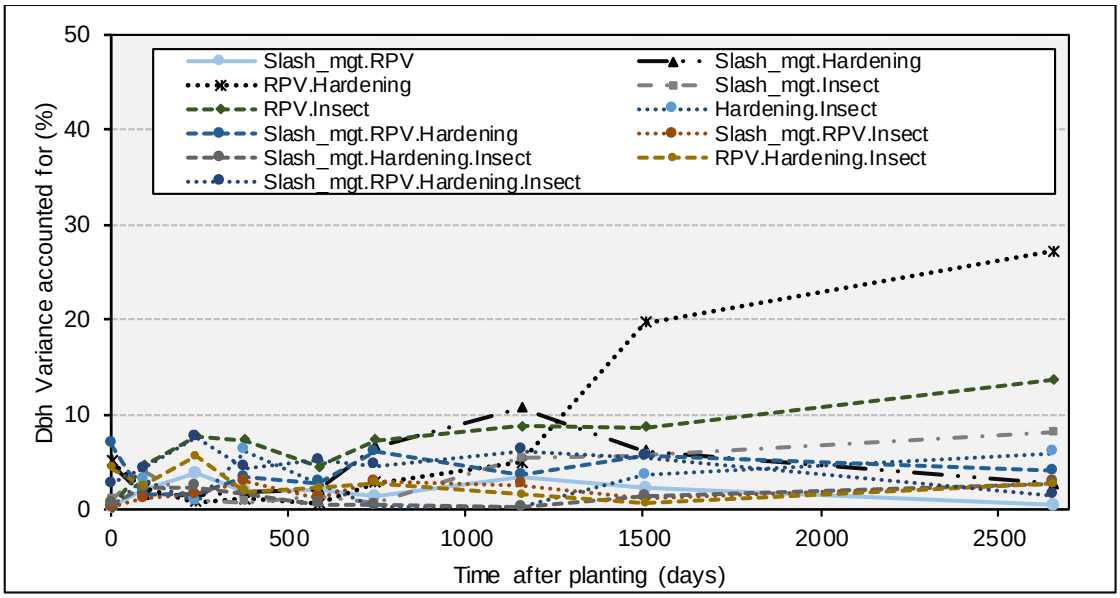

Figure 4.18: Trial D001b, variance accounted for in Gld/Dbh – Interactions

Main effects accounted for 70% (Trial D01b) in BA variance with rep explaining 18% at 6 months after planting. At 18 months, rep was responsible for 43% of BA variance, declining to 20% by Day 1156 (≈ 3 years) and 7% at end of rotation (Figure 4.19), nearly 3 times less than Trial F026 (*E.gxn*). Residue management accounted for 10% of BA variance at Day 238 (≈ 6 months), peaked at 22% by the first year and declined to 14% by 18 months (Figure 4.19). By rotation end, residue management explained 0.3% of BA variance. The comparative Trial (F026) stabilised at 13% (full rotation) with a volume = 148 m^3 ha^{-1} vs 211 m^3 ha-1 for Trial D01b.

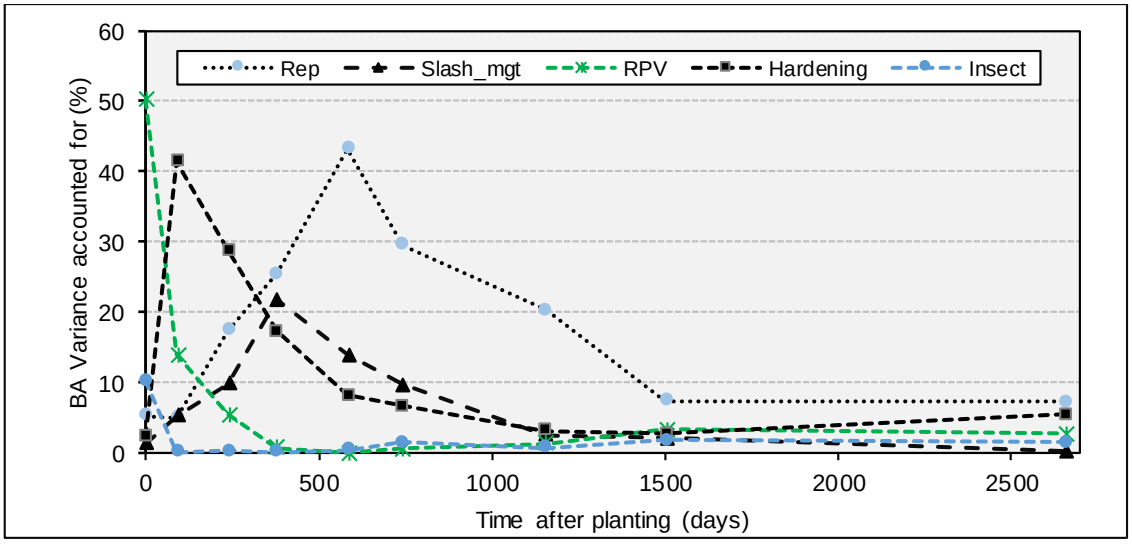

Figure 4.19: Trial D01b, accounting for variance in basal area – Main effects

Hardening accounted for 41% of basal area variance at 3 months, becoming inconsequential by full rotation at 5%. The main effect, RPV, was immediately responsible for 50% of BA variance at planting but decreased to 14% by 3 months and 5% by Day 2656 (≈7 years) (Figure 4.19). Insecticide treatment only accounted for 10% of BA variability at planting and thereafter disappeared as an explanatory variable. Two treatment interactions accounted for basal area variance; 1) residue management x hardening at 3 years (15% of variance) and 2) RPV x hardening (from 4 years to full rotation (26% variance). Where interaction effects were stronger, accounting for more than 25% of BA variance, final volume was higher, with Trial F026 = 148 m^3 ha^{-1} and Trial D01b = 211.1 m^3 ha^{-1} (Figure 4.20).

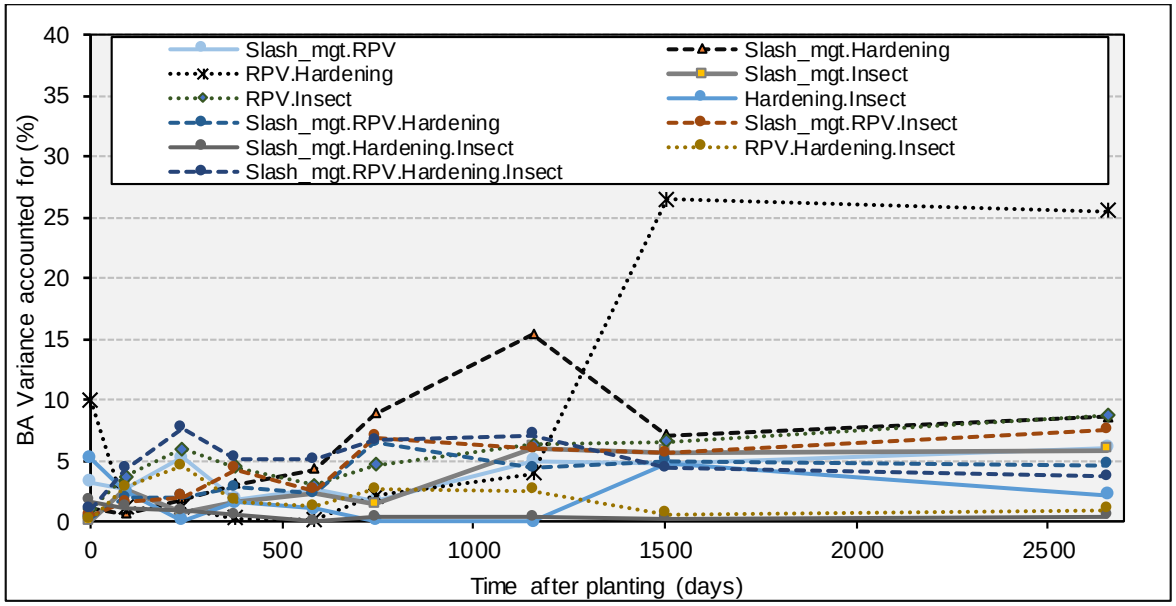

Figure 4.20: Trial D01b, variance accounted for in basal area – Interactions

4.7. RESPONSE TO SILVICULTURE TREATMENTS 14 DAYS AFTER PLANTING

The size of trial data sets limited reporting to specific periods; namely, two weeks within planting, at 12 months and final rotation. At each period, only statistically significant scores at 5% and 10% levels were discussed. The 10% confidence level was included where a trial transitioned from not significant (ns) to a 5% confidence level, with 10% reported on at a transitory period such as mid rotation. *F*- value scores at planting (Day 0) are more a reflection of nursery practices and no two or three way interaction could possibly play a role at such an early stage as insufficient growing time had passed (Table 4.19); however, *F*-values for height and Gld differences were stronger than anticipated within genotypes, *E. dunnii* and *E. gxn.* Gld, height and biomass index (Gld^2 x ht) all showed significant differences within treatments ($p < .05$) for root plug volume ($p < 0.001$) in *E. dunnii* even though efforts were made to grade according to tray size. Gld was only significant for root plug volume ($p < 0.10$) but not height. The differences in clonal Gld were more a function of

cutting dimensions at placement than early field performance. To ensure sufficient rigour and consistency of reporting, each experiment was reported on individually and thereafter combined where main or interactive effects were significant across trials.

Table 4.19: Summary of analysis of variance showing *F*-prob values for differences in plant sizes at planting (0 days). (Significance at $p < 0.05$ is in bold

Source of variation	df	*E. dunnii*						*E. grandis x E. nitens*					
		D010			E013			F026			D01b		
		Ht (m)	Gld (mm)	Bl	Ht (m)	Gld (mm)	Bl	Ht (m)	Gld (mm)	Bl	Ht (m)	Gld (mm)	Bl
Rep	3												
Slash mgt (SM)	2	0.433	0.695	0.881	0.255	0.574	0.534	0.573	0.54	0.956	0.863	0.755	0.813
Residual	6												
Plant size (PS)	1	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	**<.001**	0.312	**0.006**	0.464	**0.008**	0.095	**0.001**
Hardening (H)	1	0.099	**<.001**	**<.001**	0.446	0.083	0.226	0.776	0.767	0.872	**<.001**	0.984	**0.014**
Insecticide (I)	1	0.959	0.734	0.68	0.61	0.578	0.975	**0.035**	0.301	0.061	0.575	**0.024**	0.296
SM.PS	2	0.652	0.974	0.863	0.685	0.478	0.959	0.696	0.154	0.259	0.908	0.894	0.811
SM.H	2	0.148	0.472	0.43	0.419	0.546	0.426	0.66	0.233	0.453	0.88	0.107	0.901
PS.H	1	0.715	0.519	0.446	0.77	**0.002**	**0.006**	**0.013**	0.077	**0.048**	0.82	0.126	0.407
SM.I	2	0.042	0.804	0.754	0.617	0.312	0.149	0.976	0.795	0.862	0.6	0.614	0.914
PS.I	1	0.433	0.924	0.706	0.537	0.248	0.499	0.337	0.47	0.269	0.653	0.847	0.709
H.I	1	0.91	0.487	0.449	0.994	0.558	0.649	0.59	0.602	0.813	0.507	0.885	0.184
SM.PS.H	2	0.598	0.728	0.746	0.405	0.808	0.837	0.969	0.298	0.743	0.301	**0.044**	0.805
SM.PS.I	2	0.973	0.316	0.568	0.096	0.26	0.06	0.622	0.618	0.631	0.364	0.889	0.766
SM.H.I	2	0.849	0.988	0.978	0.916	0.62	0.989	0.762	0.983	0.876	0.77	0.757	0.853
PS.H.I	1	0.35	0.37	0.249	0.724	0.091	0.317	0.603	0.22	0.344	0.813	0.152	0.903
SM.PS.H.I	2	0.773	0.443	0.905	0.135	0.67	0.282	0.389	0.081	0.099	0.663	0.284	0.774
Residual	63												
Total	95												
Summary Statistics													
Grand mean		0.46	3.8	7.6	0.38	3.7	5.6	0.22	2.8	1.9	0.46	4.0	8.7
Standard error of differences of means (units)		0.04	0.29	1.5	0.28	0.22	0.9	0.02	0.13	0.30	0.06	0.11	2.86
Coefficient of variation (units) (%)		12.0	11.1	28.5	10.5	8.3	22.9	13.4	6.6	23.2	18.5	3.9	46.5

Note: Plant size (PS) = Root plug volume (RPV); SM = residue management

4.8. *E. DUNNII* (HIGH PRODUCTIVITY SITE) TRIAL D010 – SIGNIFICANCE IN EARLY TRIAL RESULTS

The trial analysis attempted to identify main effects and significant differences at the 5% confidence level, and as explained in the methods section, the 10% confidence level. CV values were calculated to explain the degree of precision and early trial responses are summarised below.

Root plug volume showed significant differences for height, Gld and biomass index (BI) at ($p < 0.05$), with only nursery hardening reflected at the 10% confidence level ($p < 0.10$). There were no significant interactions as measurements were completed 2 weeks after planting (Day 0). With reference to Table 4.19, *F*-values reflected the probability of differences in height for RPV, hardening (H) and the interaction of residue management with insecticide (SM x I) at the 5% levels ($p < 0.05$). Mean plant height for a large plug (105 cm^3) = 0.51 m whilst standard plug (60 cm^3) height = 0.41 m. Differences in height were significant at the 10% confidence level (nursery hardened plants = 0.45 m; not hardened = 0.47 m). CV values as an expression of precision were relatively low at 12%, with RPV accounting for 86% of variation within Gld. Although initially high, the impact of plug volume would decline with time whilst replication would increase. Mean height for burn and residue spread treatments were not significantly different for height at planting ($p < 0.05$) (Table 4.19). Burn and slash treatments were only significantly different at Day 0 ($p < 0.05$) when treated with insecticide with burn and insecticide treatments performing the best.

Gld at Day 0 (two weeks after planting) showed significant responses ($p < 0.001$) to root plug volume and nursery hardening as main effects with no interactions significant at the 95% confidence interval. The large plug (105 cm^3) Gld = 4.5 mm ± 0.06 and standard plug (60 cm^3) = 3.2 mm ± 0.06, whilst plants hardened in the nursery = 3.9 mm ± 0.06 and unhardened plants = 3.8 mm ± 0.06. Coefficient of variation (CV) as a reflection of the precision of the estimate was 11%.

Biomass index (BI) at Day 0 showed significance responses ($p < 0.001$) to RPV and nursery hardening, but with no interactions significant at 95% confidence interval. The large plug (105 cm^3) BI = 10.7 ± 0.31 and standard plug (60 cm^3) = 4.5 ± 0.31, whilst plants hardened in the nursery = 6.7 ± 0.31 and unhardened plants = 8.4 ± 0.31. The hardening of nursery plants although important to condition for field stress, did depress early growth that ultimately recovered at a later stage. CV values for BI were not as precise as for height and Gld at 29%.

4.9. *E. DUNNII* (MEDIUM PRODUCTIVITY SITE) TRIAL E013 – SIGNIFICANCE IN EARLY TRIAL RESULTS

Main effects in Trial E013 revealed responses for height to differ, with the large plug (105 cm^3) = 0.41 m and standard plug (60 cm^3) height = 0.35 m. Gld (mm) and biomass index (BI) were significant at the 95% confidence interval ($p < 0.05$) 14 days after planting whilst nursery hardening (H) as a factor was only significant for Gld at the 90% confidence interval. Interactions for root plug volume (RPV) x hardening were highly significant ($p < 0.01$) for Gld (mm) and BI whilst residue management (SM) x RPV x insecticide treatment (I) were significant at the 90% confidence interval for height (Ht) and BI (Table 4.19). The only final three way interaction to show weakly significant differences ($p < 0.10$) was RPV x nursery hardening x insecticide treatment.

Significant differences were recorded ($p < 0.05$) in plant size or RPV for height, Gld and biomass index but such responses would disappear, although RPV as a main factor would carry through to final rotation. Early responses to Gld should have been higher but were only responsive at a later stage as trees put on girth. For height measured 14 days after planting (Day 0), only RPV as a main effect was significant ($p < 0.001$) whilst the interaction of residue management x RPV x insect treatment (Slash_mgt x .PS x I) was barely significant at the 90% confidence interval. Mean plant height for a large plug (105 cm^3) = 0.41 m whilst standard plug (60 cm^3) height = 0.35 m. The factor plug size was responsible for 88% of differences in plant height due to nursery grading and selection. Although CV values, were relatively low at 11%, RPV still accounted for 88% of variation within Gld. Plug volume was expected to diminish with time whilst replication would grow in a typical Type 2 growth response.

For Gld at Day 0, only RPV ($p < 0.01$) and nursery hardening ($p = 0.083$) as main effects were significant at the 95% and 90% confidence intervals respectively, whilst the interaction RPV x hardening (PS x H) (Table 4.19) was significant at 95% confidence interval. Mean Gld for a large plug (105 cm^3) = 4.2 mm whilst standard plug (60 cm) Gld = 3.2 mm. The mean Gld for the nursery hardening treatment = 3.6 mm and no hardening or priming = 3.2 mm. Plug volume was significantly different ($p < 0.05$) whilst nursery hardening was only significant at the 10% level. The combined treatment interactions showed that the lack of hardening allowed seedlings raised in the large plug benefitted more in terms of GLD development than the standard cavity volume. Whilst plug volume was responsible for 89% of differences in Gld, grading in the nursery was based on plant height. There was a very fine margin where hardening in the nursery resulted in an initial decline in Gld. CV value for

Gld at Day 0 = 8%, indicating a very low degree of dispersion around the mean.

Biomass index measured 14 days after planting (Day 0) showed plug volume to be significant ($p < 0.001$) whilst the interaction of plug volume x hardening (PS x H) was also significant ($p < 0.05$). Mean BI for a large plug (105 cm^3) = 7.4 whilst that of the standard plug (60 cm^3) = 3.8. CV values for BI 14 days after planting revealed a much higher degree of dispersion than for either height or Gld parameters. Data for the interaction of RPV x hardening (PS x H) (Table 4.20) showed the large plug volume to be clearly superior and in the absence of hardening in the nursery (reduced irrigation) the large plug volume was able to exploit resources that were expressed in a higher biomass index.

Table 4.20: Table of means, BI 14 days after planting - Plug volume x hardening treatment interaction

Plug volume	Hardened	Not hardened
Large (105 cm^3)	6.83	7.89
Standard (60 cm^3)	3.97	3.54

($p < 0.05$; d.f = 63; se = 0.260; lsd = 0.734)

Although interactions were complex it is important to note that a large plug volume (105 cm^3) combined with the burn treatment and no insecticide application, clearly showed best early results, whilst a standard plug (60 cm^3) combined with spread residues and treated with insecticide, showed the poorest. These results were simply indicative of early establishment and would change with time.

4.10. EARLY RESPONSE - *E. GXN* (MEDIUM PRODUCTIVITY SITE) TRIAL F026 – SIGNIFICANCE IN EARLY TRIAL RESULTS

Height (Ht 0) measured 2 weeks after planting showed significant differences for the main factor, insecticide application ($p < 0.05$) and the interaction of plug volume and nursery hardening ($p < 0.05$). Clonal plug volume and hardening (water deprivation in the nursery) did not respond as significantly as in the *E. dunnii* seedling trials two weeks post planting. Mean plant height for the treatment with insecticide applied at planting (Fastac SC) = 0.22 m and where no insecticide was applied = 0.23 m. Heights measured two weeks after planting (Day 0) showed the plug volume x nursery hardening combination to be significant at the 95 % confidence interval (Figure 4.21). Coefficient of variation for height at the same time equalled 13%.

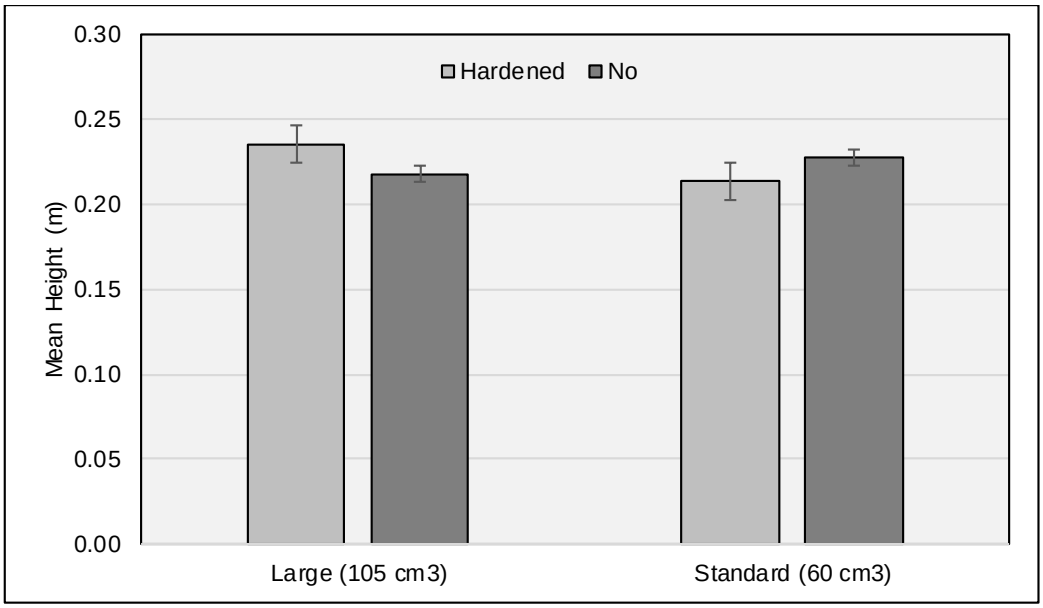

Figure 4.21: Mean height at Day 0 – RPV x nursery hardening interaction site F026 (*p* < 0.05; d.f = 29.68; se = 0.061; lsd = 0.017)

4.11. EARLY RESPONSE - *E. GXN* (HIGH PRODUCTIVITY SITE) TRIAL D01B – SIGNIFICANCE IN EARLY TRIAL RESULTS

Height (Ht 0) measured 2 weeks after planting showed significant differences for the main factors, plug volume ($p = 0.008$) and nursery hardening ($p < 0.001$). Clonal plug volume and hardening (water deprivation in the nursery) did not respond as significantly as for *E. dunnii* seedling trials two weeks after establishment. Mean plant height for the large plug (105 cm^3) = 0.5 m and standard plug (60 cm^3) = 0.4 m. The CV value for height at Day 0 = 19%, indicating a higher degree of dispersion of measures around the mean than for the previous three trials.

For Gld measured at Day 0, the application of insecticide ($p = 0.024$) was significant. Mean plant Gld for the large plug (105 cm^3) = 4.0 mm and standard plug (60 cm^3) = 4.1 mm whilst the CV = 4%, was indicative of high uniformity. Mean plant height remained unaffected by the application of insecticide and both were equal to 4.0 mm. The low level of significance for Gld and height indicated that 14 days after planting was too early a period in which to determine an early response and should not be measured before 12 months when height is more responsive. Biomass index measured 14 days after establishment revealed plug volume ($p = 0.001$) and nursery hardening ($p = 0.014$) to be the only significant factors. Mean plant BI for the large plug (105 cm^3) = 10.1 and standard plug (60 cm^3) = 7, with a CV = 47%, indicating a very high dispersion around the mean as opposed to all three previous CV values.

4.12. TRIAL RESPONSES AT 12 MONTHS

F- values at 12 months after planting showed stronger responses for main factors and their silviculture interactions (Table 4.21). Although canopy closure did not occur until 15 months for *E. dunnii* and 18 months for *E. gxn*, 12 months is an accepted operational threshold when no further silviculture interventions will mitigate against poor stocking, uniformity or growth and a decision to either cut the standing crop to waste or allow it to continue to full rotation must be considered. The benefits of good nursery practices, large plug volume and hardening would still be apparent and physiological measures of stomatal conductance and chlorophyll content indicative of the general vigour. Table 4.21 is a summation of the analysis of variance (ANOVA) showing *F-prob* values for differences in tree size and stocking at 12 months. Significance at $p < 0.05$ is shaded and bold font, with $p < 0.10$ (weakly significant) shaded. Morphological measures of height (m), Dbh (cm), stocking (Spha) and basal area ($m^2 ha^{-1}$) were presented where there were significant differences up to the 90% confidence interval for individual trials.

4.12.1. 12 MONTH MEASURE - HIGH PRODUCTIVITY SITE (TRIAL D010)

For Dbh at 12 months, residue management x RPV ($p = 0.008$) was the only significant interaction amongst factors (Figure 4.22). For the factor residue management, burning, revealed the best Dbh performance across both plug sizes. Mean Dbh for residue management treatments were burning = 4.5 cm, mulch = 4.2 cm and spread residue = 4.3 cm. The CV value for Dbh at 12 months was 11% indicating a low degree of dispersion of Dbh measures around the mean.

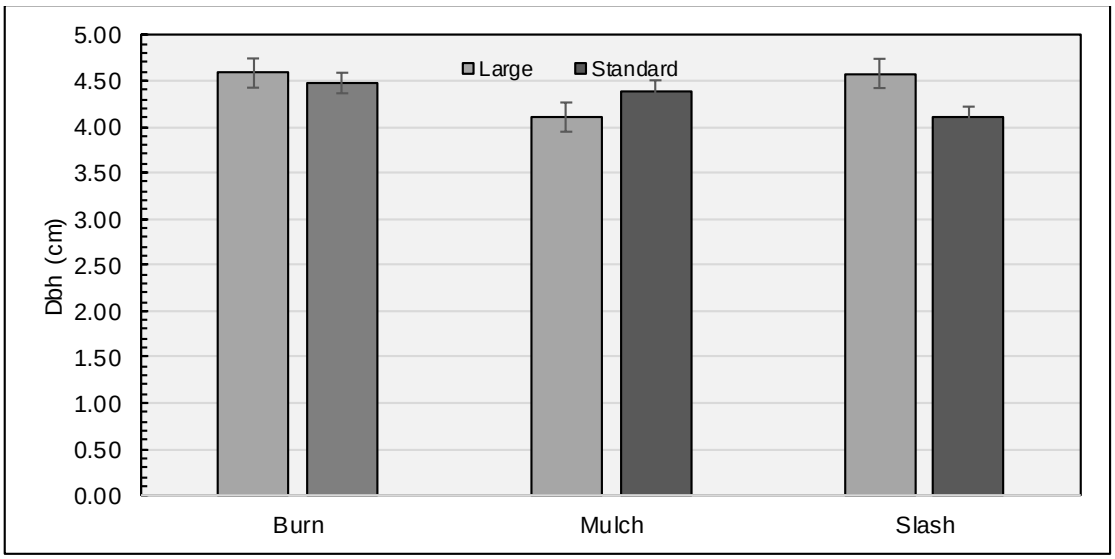

Figure 4.22: Mean Dbh (cm) at 12 months, Site D010 – RPV x residue management interaction ($p < 0.05$; d.f = 11.65; se = 0.0937; lsd = 0.4817)

Stocking at 12 months was to appear for the first time in the trial series as weakly significant for the interaction of RPV x hardening (p = 0.09), but worthy of inclusion as no further interactions were significant and stocking has a major impact on final volume. A combination of the treatments, large plug volume (105 cm^3) and nursery hardening produced the highest stocking at 12 months (1644 Spha) with the lowest stocking for the treatment of a standard plug (60 cm^3) volume hardened in the nursery through water deprivation (1582 Spha). The CV value for stocking = 7% (Figure 4.23).

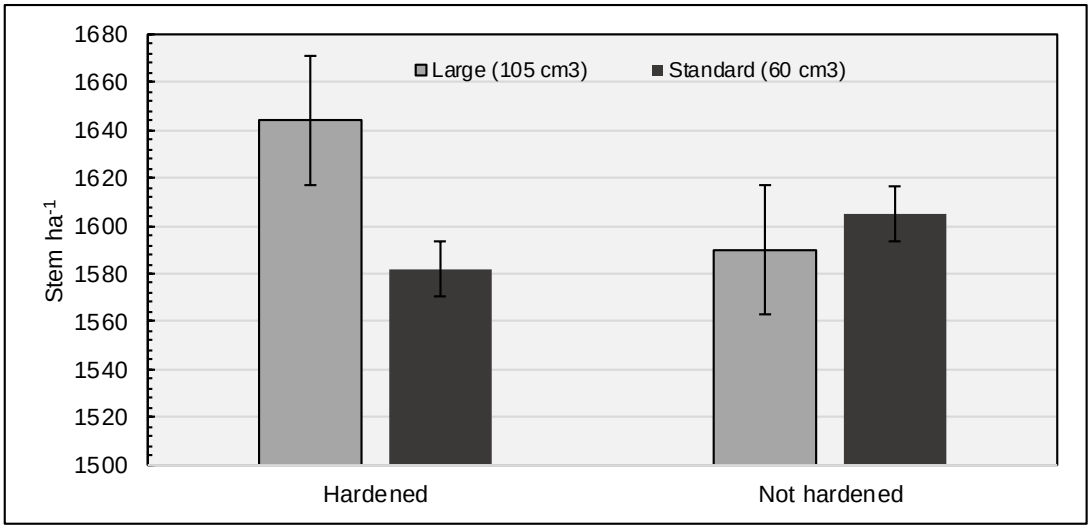

Figure 4.23: Mean stocking (Spha) at 12 months, Site D010 – Plug size x hardening interaction (p < 0.10; df = 63; se = 22.4; lsd = 63.4)

Table 4.21: Summary of analysis of variance showing *F-prob* values for differences in tree size and stocking at 12 months. Significance at $p < 0.05$ in bold. Note: Plant size (PS) = Root plug volume (RPV); SM = residue management

Source of variation	df	*E. dunnii*								*E. grandis x E. nitens*							
		D010				E013				F026				D01b			
		Ht (m)	Dbh (cm)	Stock (sph)	BA ($m^2 ha^{-1}$)	Ht (m)	Dbh (cm)	Stock (sph)	BA ($m^2 ha^{-1}$)	Ht (m)	Dbh (cm)	Stock (sph)	BA ($m^2 ha^{-1}$)	Ht (m)	Dbh (cm)	Stock (sph)	BA ($m^2 ha^{-1}$)
Rep	3																
Slash mgt (SM)	2	0.098	0.37	0.228	0.228	**0.006**	**0.008**	0.266	**0.009**	**0.02**	**0.013**	0.063	**0.014**	0.371	0.054	0.163	**0.05**
Residual	6																
Plant size (PS)	1	0.834	0.318	0.306	0.222	**0.008**	**<.001**	0.277	**<.001**	**<.001**	**<.001**	0.063	**<.001**	0.935	0.544	0.351	0.633
Hardening (H)	1	0.687	0.709	0.494	0.613	0.39	0.307	0.64	0.296	**0.047**	**0.021**	0.098	**0.005**	**0.01**	**0.029**	0.534	**0.02**
Insecticide (I)	1	0.697	0.944	0.732	0.945	0.551	0.731	0.277	0.522	0.502	0.868	0.212	0.637	1	0.65	0.755	0.836
SM.PS	2	0.059	**0.008**	0.915	**0.028**	0.96	0.829	0.176	0.969	0.915	0.655	0.906	0.984	0.117	0.499	0.39	0.55
SM.H	2	0.15	0.292	0.814	0.53	0.589	0.733	0.52	0.827	0.31	0.327	0.926	0.673	0.25	0.527	0.729	0.37
PS.H	1	0.253	0.89	**0.09**	0.377	0.709	0.932	0.876	0.819	0.866	0.75	1	0.525	0.775	0.532	0.534	0.767
SM.I	2	0.468	0.585	0.682	0.822	0.42	0.49	0.728	0.411	0.726	0.963	0.794	0.713	0.547	0.739	0.729	0.579
PS.I	1	0.285	0.28	1	0.334	0.297	0.522	0.64	0.417	0.726	0.189	0.404	0.63	0.456	0.104	0.755	0.23
H.I	1	0.783	0.536	0.732	0.597	0.954	0.941	0.437	0.593	0.161	**0.05**	0.834	0.072	0.235	0.135	0.215	0.474
SM.PS.H	2	0.219	0.139	0.124	0.393	0.554	0.942	0.728	0.967	0.643	0.494	0.794	0.525	0.696	0.29	0.843	0.401
SM.PS.I	2	0.772	0.894	0.322	0.992	0.662	0.897	0.929	0.811	0.996	0.731	0.372	0.819	0.514	0.35	0.153	0.252
SM.H.I	2	0.904	0.375	0.573	0.376	0.679	0.481	0.308	0.362	0.491	0.687	0.867	0.97	0.771	0.533	0.546	0.852
PS.H.I	1	0.944	0.748	0.494	0.765	0.652	0.535	0.876	0.62	0.847	0.948	**0.024**	0.059	0.689	0.4	1	0.464
SM.PS.H.I	2	0.216	0.387	0.971	0.399	0.902	0.634	0.472	0.494	0.766	0.803	0.174	0.619	0.409	0.203	0.222	0.193
Residual	63																
Total	95																
Summary Statistics																	
Grand mean		4.4	4.4	1605	2.6	3.6	3.5	1584	1.7	2.7	4.2	1439	2.06	2.3	4.1	1601	2.23
Standard error of means (units)		0.22	0.33	77.7	0.39	0.27	0.37	85.4	0.33	0.20	0.21	127.2	0.61	0.22	0.34	85.4	0.37
Coefficient of variation (units) (%)		7.2	10.8	6.8	21.6	10.6	14.8	7.6	27.0	10.5	7.1	12.5	17.4	13.3	11.9	7.5	23.6

Only one treatment interaction of residue management x RPV (SM x PS) was significant ($p < 0.05$) for basal area (m^2 ha^{-1}). The CV value for BA = 22% indicated a fair degree of dispersion around the mean for the interaction of RPV x residue management (Figure 4.24).

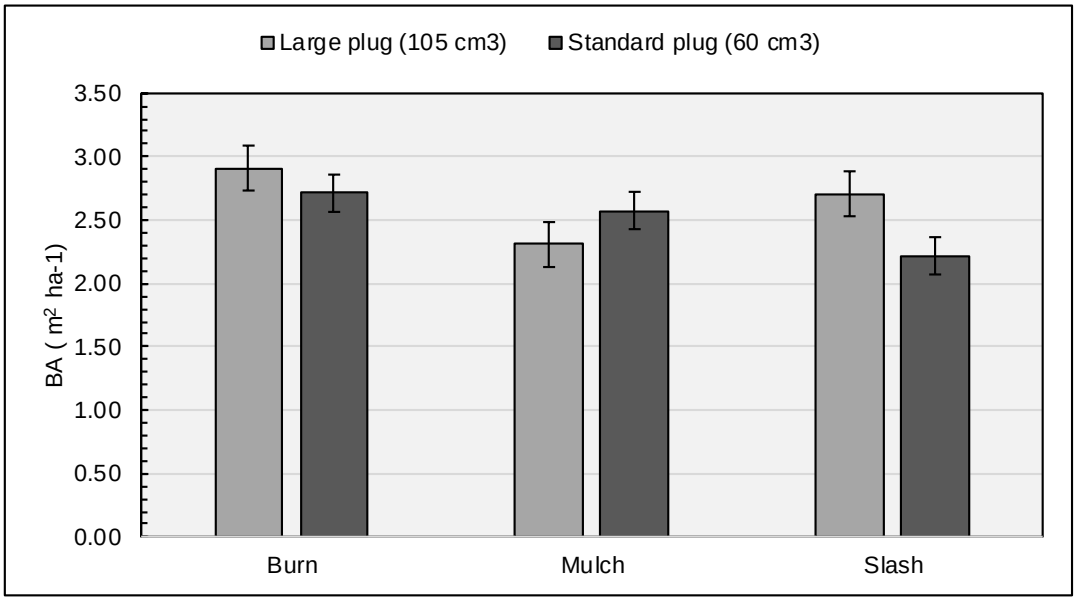

Figure 4.24: Mean Basal area (m^2 ha^{-1}) at 12 months (Site D010) for the residue management x RPV ($p < 0.05$; df = 12.02; se = 0.1795; lsd = 0.5330)

At 12 months the burn treatment showed the best BA across plug sizes (large plug (105 cm^3) = 2.9 m^2 ha^{-1} and standard plug (60 cm^3) = 2.7 m^2 ha^{-1}.

Crown diameter, stomatal conductance and chlorophyll content were reported on at 12 months (Table 4.22). Of the four trials, two *E. dunnii* trials (high and medium productivity) and one *E. gxn* trial (medium productivity) showed significant differences at the 5% level. T-tests within the ANOVA to control the Type-1 error rate (probability of rejecting the null hypothesis given that it is true) were calculated and comparisons significant at the 5% level highlighted (*).

Table 4.22: Summary of analysis of variance showing *F-prob* values for crown diameter (m) at 12 months (Significance at $p < 0.05$ is in bold)

Source of variation	df	*E. dunnii*		*E. grandis x E. nitens*	
		D010	E013	F026	D01b
Rep	3				
Slash mgt (SM)	2	**0.046**	**0.008**	**0.046**	0.961
Residual	6				
Plant size (PS)	1	0.713	0.071	**0.006**	0.634
Hardening (H)	1	0.457	0.227	0.169	0.073
Insecticide (I)	1	0.480	0.301	0.644	0.750
SM.PS	2	0.257	0.927	0.649	0.151
SM.H	2	0.257	0.518	0.629	**0.026**
PS.H	1	0.887	0.315	0.616	0.388
SM.I	2	0.612	0.874	0.808	0.980
PS.I	1	0.501	0.921	0.781	0.987
H.I	1	0.578	0.417	0.112	0.271
SM.PS.H	2	0.341	0.418	0.586	0.542
SM.PS.I	2	0.135	0.866	0.949	0.737
SM.H.I	2	0.417	0.665	0.764	0.850
PS.H.I	1	0.282	0.963	0.794	0.574
SM.PS.H.I	2	0.429	0.666	0.676	0.807
Residual	63				
Total	95				
Summary Statistics					
Grand mean		1.32	1.13	0.97	0.744
Standard error of differences of means (units)		0.075	0.927	0.174	0.13
Coefficient of variation (units) (%)		8.0	11.6	25.2	25.4

Canopy diameter responded positively to burning of residues whilst mulch and spread residues showed no significant differences, which tends to reinforce the possibility that positive responses to crown diameter under burn treatments are linked to nutrient availability and less so to water deficits between residue treatments (Table 4.22).

Stomatal conductance measurements showed a rapid decline from a mean of 423 $mmolm^{-2}s^{-1}$ at 3 months to recordings at 12 months. Twelve 12 month measurements were very low and may have been a reflection of the time of day, around 08H00, when recordings were taken, or the actual position on the tree where measured. However, all measurements at 12 months were consistently low with a trial mean = 21 $mmolm^{-2}s^{-1}$. Stomatal conductance

measurements at 24 months showed a similar trial mean = 28 mmolm^{-2}s^{-1}. Stomatal conductance was not significant at the 95% confidence interval for residue treatments but was weakly significant (p = 0.069) for plug volume (RPV) at 12 months and hence was elucidated further (Table 4.23). The large plug volume (105 cm^3) revealed a greater stomatal conductance = 22.5 mmolm^{-2}s^{-1}, whilst the standard plug recorded a mean stomatal conductance = 19.8 mmolm^{-2}s^{-1}. The effects of hardening of plant stock in the nursery had dissipated by 12 months and there were no significant differences for the hardening treatment (p = 0.948). It is therefore safe to assume that stomatal conductance as a measure of physiological vigour is only of value from establishment to just before canopy closure in terms of treatment effects and the position of measurements on the crown absolutely critical.

Table 4.23: Summary ANOVA showing *F-prob* values for stomatal conductance (mmolm^{-2}s^{-1}) at 12 months (Significance at p < 0.10 in bold)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	1516.45	505.48	2.75	
Rep.Slash_mgt stratum					
Slash_mgt	2	593.68	296.84	1.61	0.275
Residual	6	1103.13	183.85	3.86	
Rep.Slash_mgt.*Units* stratum					
RPV	**1**	**163.10**	**163.10**	**3.42**	**0.069**
Hardening	1	0.21	0.21	0.00	0.948
Insect	1	36.37	36.37	0.76	0.385
Slash_mgt.RPV	2	138.22	69.11	1.45	0.242
Slash_mgt.Hardening	2	59.72	29.86	0.63	0.537
RPV.Hardening	1	4.98	4.98	0.10	0.747
Slash_mgt.Insect	2	76.39	38.19	0.80	0.453
RPV.Insect	1	0.49	0.49	0.01	0.919
Hardening.Insect	1	26.55	26.55	0.56	0.458
Slash_mgt.RPV.Hardening	2	84.42	42.21	0.89	0.417
Slash_mgt.RPV.Insect	2	57.66	28.83	0.61	0.549
Slash_mgt.Hardening.Insect	2	10.58	5.29	0.11	0.895
RPV.Hardening.Insect	1	17.29	17.29	0.36	0.549
Slash_mgt.RPV.Hardening.Insect	2	106.84	53.42	1.12	0.332
Residual	63	3000.30	47.62		
Total	95	6996.39			

Root plug volume x insecticide treatment (Figure 4.25; Table 4.24) (p = 0.045) and residue management x RPV x hardening (Figure 4.26) treatment (p = 0.018) accounted for significant differences in chlorophyll content index (CCI) at 12 months. A large plug (105 cm^3) combined with insecticide showed the most vigour in terms of CCI (34.5) whilst the standard plug (60 cm^3) combined with insecticide performed lower and hence it was assumed that plug volume was of greater relevance to overall plant vigour than insecticide application.

Table 4.24: Summary of analysis of variance showing *F-prob* values for chlorophyll conductance (CCI) (Significance at $p < 0.05$ in bold)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	125.259	41.753	2.00	
Rep.Slash_mgt stratum					
Slash_mgt	2	21.951	10.975	0.53	0.616
Residual	6	125.010	20.835	2.59	
Rep.Slash_mgt.*Units* stratum					
RPV	1	13.764	13.764	1.71	0.195
Hardening	1	0.177	0.177	0.02	0.883
Insect	1	2.608	2.608	0.32	0.571
Slash_mgt.RPV	2	3.932	1.966	0.24	0.784
Slash_mgt.Hardening	2	31.310	15.655	1.95	0.151
RPV.Hardening	1	2.260	2.260	0.28	0.598
Slash_mgt.Insect	2	13.926	6.963	0.87	0.426
RPV.Insect	**1**	**33.705**	**33.705**	**4.19**	**0.045**
Hardening.Insect	1	5.518	5.518	0.69	0.411
Slash_mgt.RPV.Hardening	**2**	**68.762**	**34.381**	**4.28**	**0.018**
Slash_mgt.RPV.Insect	2	11.556	5.778	0.72	0.491
Slash_mgt.Hardening.Insect	2	52.771	26.385	3.28	0.044
RPV.Hardening.Insect	1	1.179	1.179	0.15	0.703
Slash_mgt.RPV.Hardening.Insect	2	10.806	5.403	0.67	0.514
Residual	63	506.481	8.039		
Total	95	1030.975			

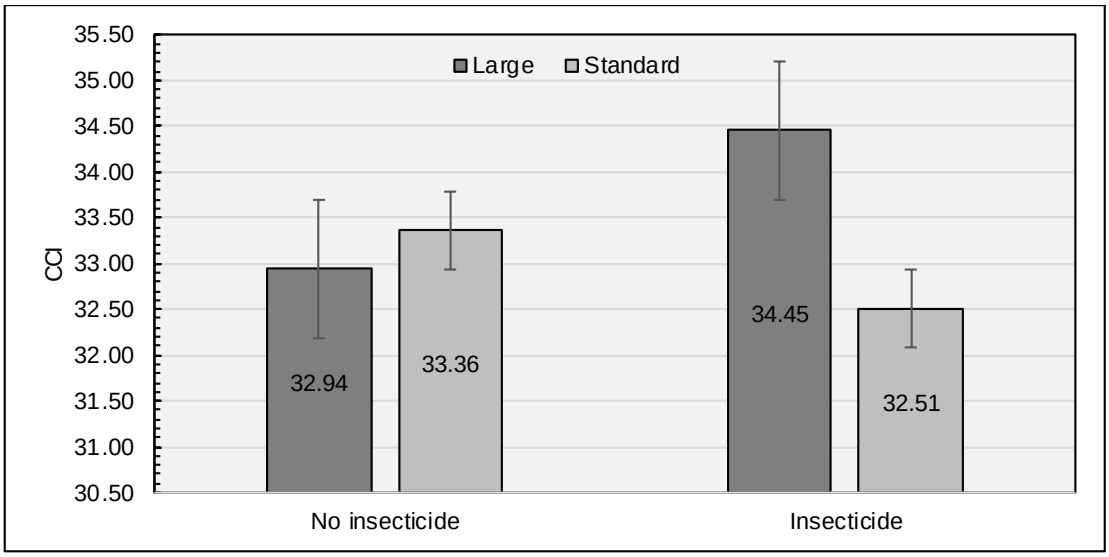

Figure 4.25: Mean chlorophyll content index (CCI), Site D010, at 12 months for the interaction of RPV x Insecticide treatment ($p < 0.05$)

At a more complex three way interaction, a combination of burnt residue x hardening x large plug volume (105 cm^3) showed the highest CCI score but was only slightly higher than (difference = 0.2) the next score for a large plug x not hardened x spread residue (Figure 4.26). The impact of nursery hardening is unlikely to have influenced the chlorophyll content index and the only common factor was the large plug volume. The value of CCI as an indicator of plant vigour in short rotation eucalypts remained questionable throughout the trial series; however, all four trials were compared to determine whether an acceptable hypothesis could be formulated with no significant CCI response to main effects or the interaction thereof expected.

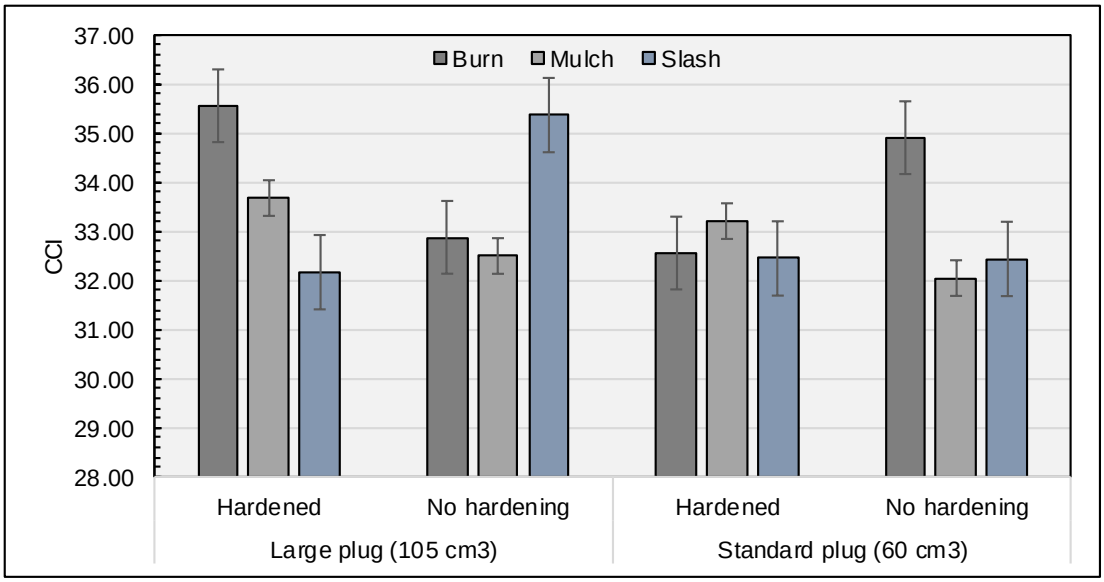

Figure 4.26: Mean chlorophyll content index (CCI) at 12 months, Site D010, for the interaction of residue management x RPV x hardening treatment ($p < 0.05$)

4.12.2. 12 MONTH MEASURE – MEDIUM PRODUCTIVITY SITE (TRIAL E013)

Two factors proved significant (p <0.05) for basal area at 12 months, residue management (SM) (Table 4.21) (p = 0.009) and RPV (p < 0.001) (Figure 4.27). Burning proved significantly more responsive (p < 0.05) than spread and mulch treatments whilst CV = 22% indicating a high degree of dispersion around the mean for residue treatments. The large plug volume also showed significantly superior BA growth at 12 months. Similar results were recorded for height and Dbh for these treatments and were not reported further as basal area was already discussed.

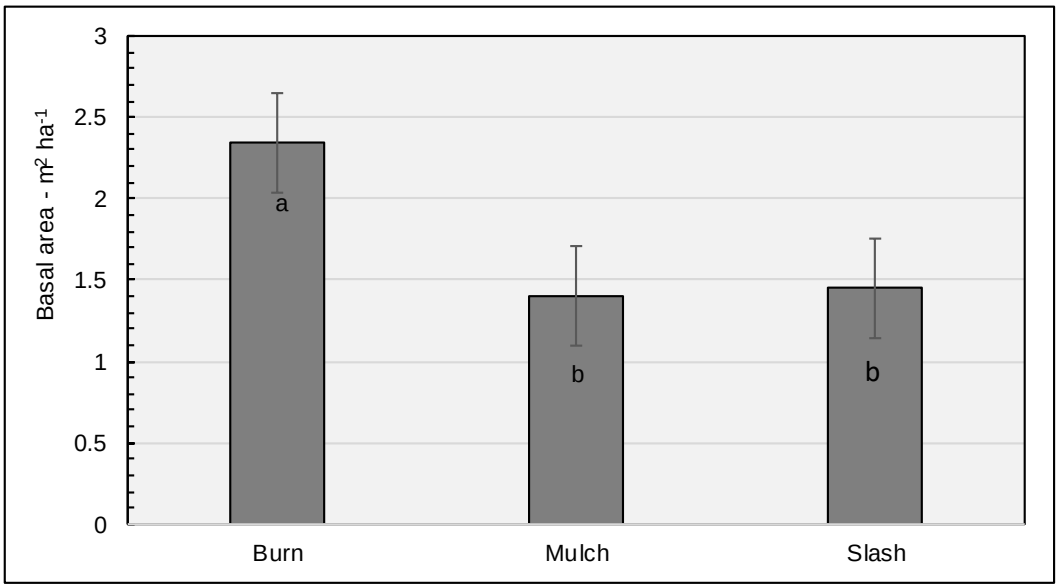

Figure 4.27: Mean basal area (BA) (m^2 ha^{-1}) at 12 months, Site E013, for residue management (p < 0.05; df = 6; se = 0.1586; lsd = 0.5487). Means with the same letter are not significantly different.

Crown diameter at 12 months (calculated by averaging crown width measurements at right angles) was compared as a function of tree performance and overall vigour. Two factors showed significant effects for crown diameter at 12 months (site E013), residue management (p = 0.008) and plug volume (p < 0.071). Plug volume was only significant at the 10% level with crown diameters close to equal. The burn treatment (crown dia. = 1.3 m) proved to be significantly higher (p < 0.05) than the spread (crown dia. = 1.1 m) and mulch (crown dia. = 1.0 m) treatments with a crown diameter CV = 6%. Crown diameter at 12 months on burn treatments benefitted from increased height and Dbh as opposed to mulch and slash spread sites.

Stomatal conductance at 12 months was weakly significant for residue management (p = 0.063) and hardening (p = 0.087). However, there was a significant effect for residue management x hardening x insecticide (p = 0.034). Virtually all of the grey bars (Figure 4.28)

were similar with the blue bars for burning higher in terms of stomatal conductance scores. Residue management and hardening were only significant at the 10% confidence level as main factors. With a CV value = 30%, the dispersion around the mean was high with measures possibly reflecting a spread indicative of the time taken to complete stomatal readings; however, the burn treatment expressed the highest stomatal conductance rate (Figure 4.28). With previous measures for growth, basal area and crown diameter all showing favourable responses to burning, the high stomatal conductance rate should not be interpreted as an indication of stress but rather the result of active biomass accumulation in a healthy performing timber stand with soil moisture and nutrients not limited.

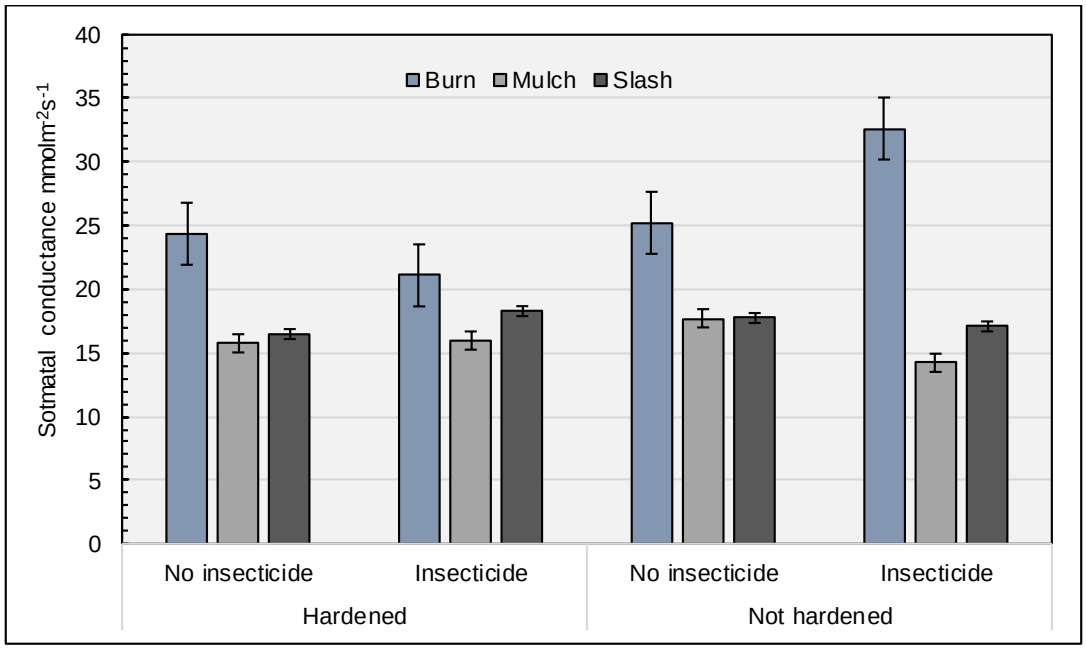

Figure 4.28: Mean stomatal conductance (mmolm^{-2} s^{-1}), Site E013, at 12 months for residue x hardening x insecticide application treatment (p < 0.05; df = 13.68; se = 3.10; lsd = 9.416)

The only factor significant for chlorophyll conductance (CCI) at 12 months was hardening of nursery stock (p = 0.040). Hardened stock where water deprivation was applied = 35.4 whilst plants that were watered consistently (not hardened) = 37.2. Hence, the application of hardening still recorded reduced CCI scores up to a year later but not to the detriment of plant vigour. The role of a chlorophyll content index in the context of these trials appears to be more applicable in a controlled environment.

4.12.3. 12 MONTH MEASURE – MEDIUM PRODUCTIVITY SITE (TRIAL F026)

Height at 12 months (Table 4.21) (Site F026 - *E. gxn* clone) showed significant differences for three separate factors, residue management (p = 0.020), root plug volume (p < 0.001) and nursery hardening (p = 0.047). The large plug (105 cm^3) = 2.8 m whilst the standard

plug (60 cm^3) = 2.6 m. The hardening treatment revealed that water regulation in the nursery resulted in shorter plants across all plug volumes with the hardened treatment = 2.6 m and standard watering = 2.7 m. Residue management responses for Trial F026 showed the same significant differences at 12 months as the *E. dunnii* trials. The burn treatment proved to be the best performing (Figure 4.29); however, mulching replaced spread residues as the next best rank.

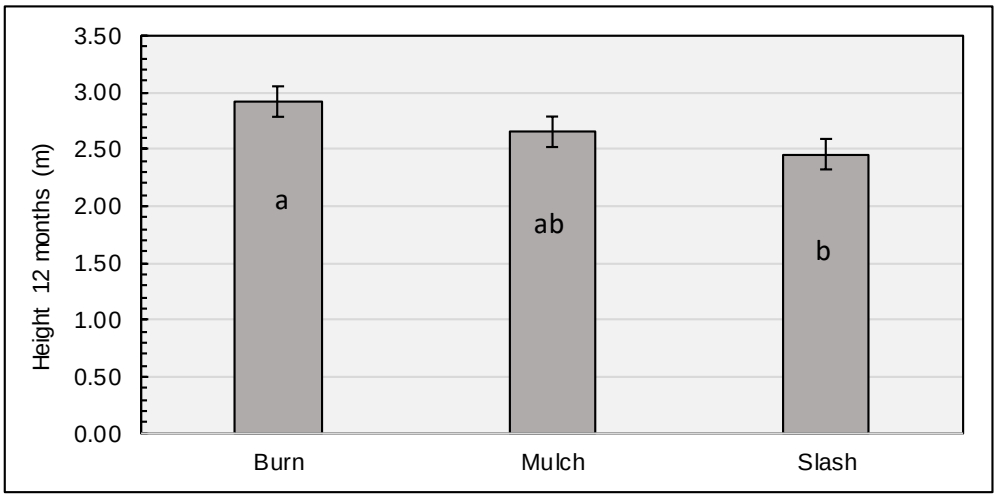

Figure 4.29: Mean height (m) at 12 months, Site F026, for residue management treatment ($p < 0.05$; df = 6; se = 0.0823; lsd = 0.285). Means with the same letter are not significantly different

Stocking at 12 months expressed weakly significant treatment effects (10% level) for residue management ($p = 0.063$) and RPV ($p = 0.063$), whilst plug volume x hardening x insecticide ($p = 0.024$) was significant at the 95% confidence interval (Figure 4.30).

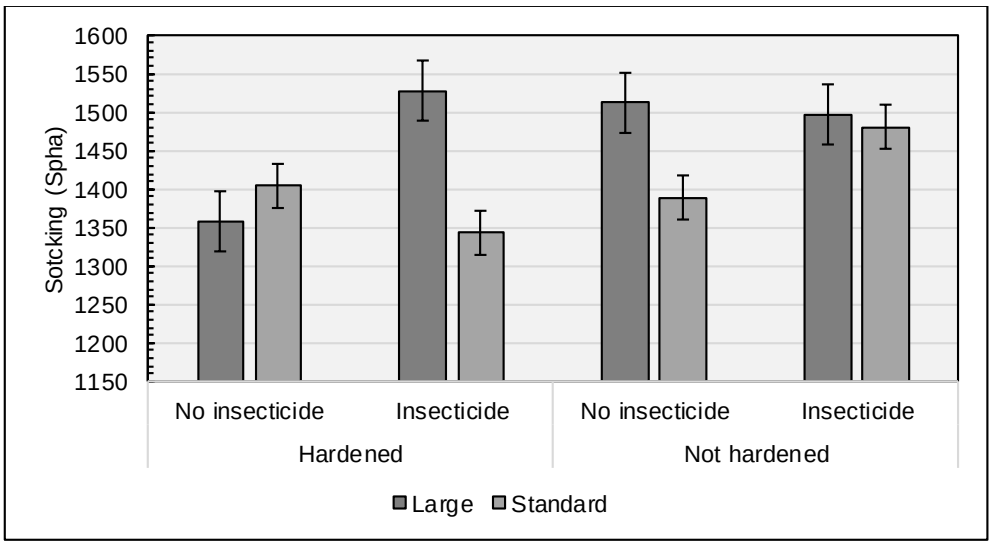

Figure 4.30: Mean stocking (Spha) at 12 months, Site F026, RPV x hardening x insecticide treatment combination ($p < 0.05$; d.f = 63; se = 52; lsd = 147)

Within the interaction of plug volume x hardening x insecticide treatment, the large plug volume (105 cm^3), hardened in the nursery and treated with insecticide (Fastac (SC) produced a mean stocking level = 1528 spha at 12 months (Figure 4.30). The next two best stocking levels were for treatments of a large plug volume (105 cm^3) and not hardened in the nursery (± 1500 spha).

Three main factors were significant for basal area (BA) at 12 months, 1) residue management (p = 0.014), 2) plug volume (p < 0.001), and 3) hardening (p = 0.005). One interaction, namely plug volume x hardening x insecticide (p = 0.059) showed significance. Burning produced a significantly higher basal area than mulch and spread (Figure 4.31) with the CV value = 12% for BA revealing a low degree of dispersion around the mean.

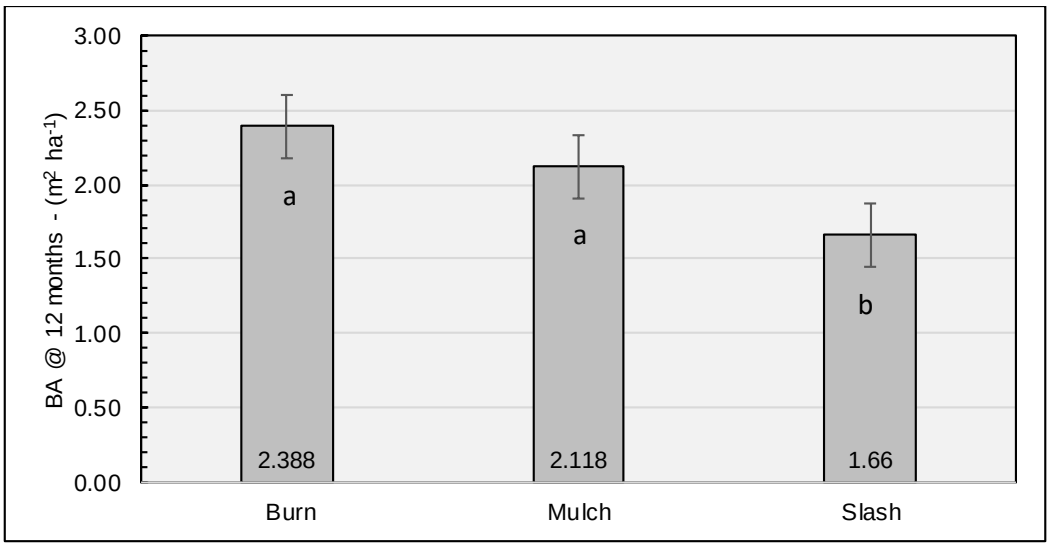

Figure 4.31: Mean basal area (BA) (m^2 ha^{-1}) at 12 months, Site F026, for residue management (p < 0.05; df = 6; se = 0.1586; lsd = 0.5487). Means with the same letter are not significantly different.

Plug volume was significant (p < 0.001) in terms of BA with the large plug volume (105 cm^3) = 2.2 m^2 ha^{-1} and standard plug (60 cm^3) = 1.9 m^2 ha^{-1}. Hardening proved to be significant (p = 0.005) although differences between treatments were small, with hardened = 2.23 m^2 ha^{-1} and not hardened = 2.16 m^2 ha^{-1}. Basal area for plug volume x hardening x insecticide at 12 months was primarily driven by a large plug volume consistently outperforming the standard plug, whilst hardening also showed some benefits where treatments were not water deprived in the nursery. In summary, a large well-conditioned nursery plant outperformed the hardened counterpart and always outperformed the standard plug volume (60 cm^3) at 12 months (Figure 4.32).

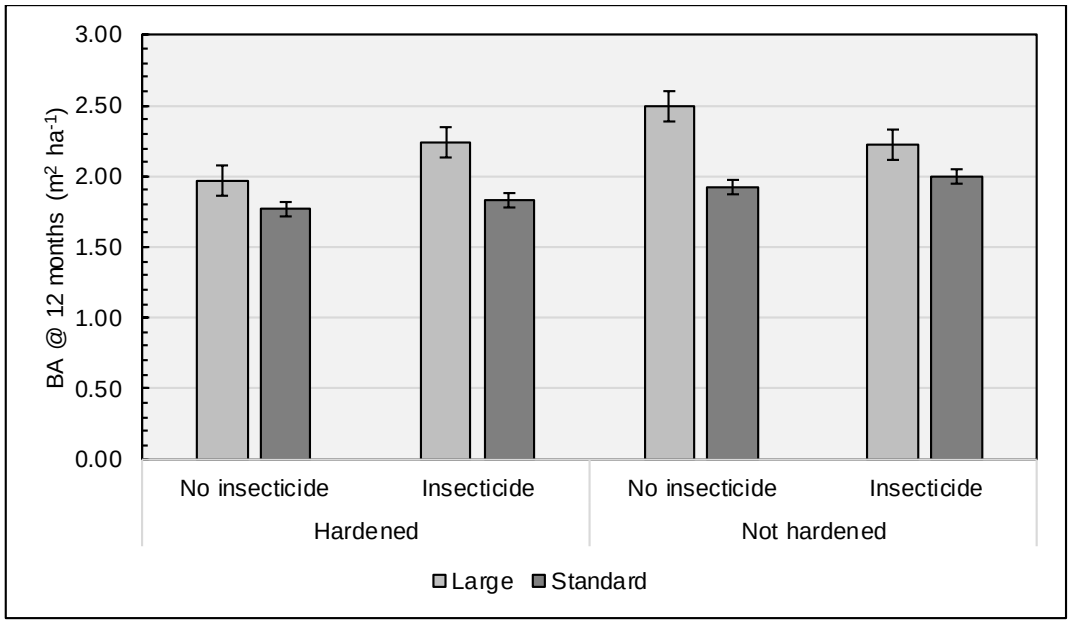

Figure 4.32: Mean basal area (BA) (m^2 ha^{-1}) at 12 months, Site F026, for RPV x Hardening x Insecticde treatment ($p < 0.05$; df = 63; se = 0.1019; lsd = 0.2880)

Two factors proved significant for crown diameter at 12 months, 1) residue management (p = 0.046) and 2) plug volume (p = 0.006). Crown diameter for the large plug volume = 1.0 m with crown diameter for the standard plug volume = 0.9 m. The burn treatment (dia. = 1.1 m) proved to be significantly higher ($p < 0.05$) than the spread residues (dia. = 0.8 m) and mulch (dia. = 1.0 m) treatments with the CV value at 12 months for crown diameter = 15%, not nearly as precise as the *E. dunnii* trials at the same period. Crown diameter at 12 months on burn treatments appeared to have benefitted from increased height and Dbh, as opposed to the mulch treatment, whilst the crown diameter on the spread residue site was nearly 42% lower than the burnt treatment.

Stomatal conductance at 12 months showed significant differences for the combined treatment of plug volume x nursery hardening x insecticide application (p = 0.018) (Table 4.25; Figure 4.33). The spread of treatment means was much lower although statistically significant with a CV value = 18%.

Table 4.25: Summary of analysis of variance (F026) showing *F-prob* values for stomatal conductance ($mmolm^{-2}s^{-1}$) at 12 months (Significance at $p < 0.10$ in bold)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	63.504	21.168	3.11	
Rep.Slash_Mgt stratum					
Slash_Mgt	2	17.047	8.524	1.25	0.352
Residual	6	40.894	6.816	1.08	
Rep.Slash_Mgt.*Units* stratum					
RPV	1	5.741	5.741	0.91	0.345
Hardening	1	0.136	0.136	0.02	0.884
Insect	1	3.150	3.150	0.50	0.483
Slash_Mgt.RPV	2	4.921	2.461	0.39	0.680
Slash_Mgt.Hardening	2	24.778	12.389	1.96	0.150
RPV.Hardening	1	3.359	3.359	0.53	0.469
Slash_Mgt.Insect	2	2.053	1.027	0.16	0.851
RPV.Insect	1	8.192	8.192	1.29	0.260
Hardening.Insect	1	0.046	0.046	0.01	0.933
Slash_Mgt.RPV.Hardening	2	1.355	0.678	0.11	0.899
Slash_Mgt.RPV.Insect	2	1.499	0.749	0.12	0.889
Slash_Mgt.Hardening.Insect	2	7.492	3.746	0.59	0.556
RPV.Hardening.Insect	**1**	**37.072**	**37.072**	**5.85**	**0.018**
Slash_Mgt.RPV.Hardening.Insect	2	8.344	4.172	0.66	0.521
Residual	63	398.906	6.332		
Total	95	628.490			

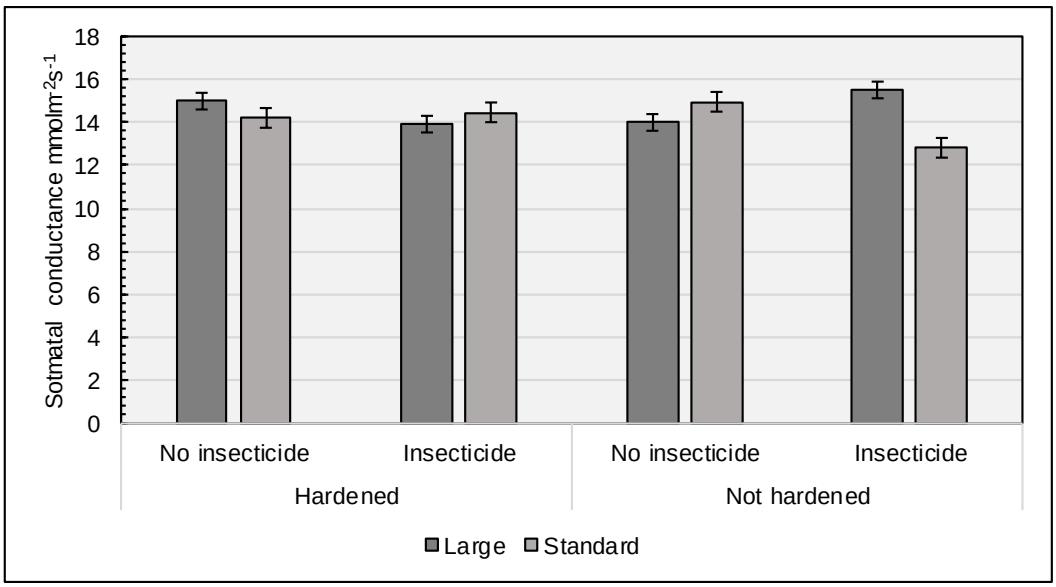

Figure 4.33: Trial F026 - Mean stomatal conductance ($mmolm^{-2}s^{-1}$) at 12 months for RPV x hardening x insecticide application treatment ($p < 0.05$; df = 63; se = 0.726; lsd = 2.053)

A combination of large plug volume x insecticide x not hardened (Figure 4.33) produced the highest stomatal conductance score = 15.5 $mmolm^{-2}s^{-1}$ whilst the exact same combination of insecticide application and no hardening scored the lowest for a standard plug volume (60 cm^3) at 12.8 $mmolm^{-2}s^{-1}$. As for the previous trials, 12 month measurements for stomatal conductance remained consistently low. Reasons for such low readings were previously addressed and not discussed further. The only treatment that was significant for chlorophyll conductance (CCI) at 12 months was a combination of residue management and insecticide (p = 0.045) with a CV score = 11%. The most noteworthy point was that the highest CCI score (44.0) and lowest score (40.2) both emanated from the exact same treatment.

4.12.4. 12 MONTH MEASURE – HIGH PRODUCTIVITY SITE (TRIAL D01B)

Height at 12 months, Site D01b - *E. gxn* clone, showed significant differences (Table 4.21) for one treatment, nursery hardening (p = 0.01). Trial results highlighted that water deprivation in the nursery aimed at improving initial survival can have a negative impact on height growth. The application of the nursery hardening resulted in a mean height = 2.2 m, whilst no hardening = 2.4 m.

Dbh at 12 months showed significant differences for 1) residue management (p = 0.054) and 2) nursery hardening (p = 0.029). Residue management responded differently to the seedling (*E. dunnii*) trials with the following mean Dbh recorded, burning = 4.2 cm, mulch = 4.2 cm and spread residue = 3.8 cm. Burning did not rank highest for residue management but differences between the treatments were low. The CV value for Dbh at 12 months = 6% indicating a high degree of precision in comparison to *E. dunnii* Dbh measures. Nursery hardening, although significantly different (p = 0.029), recorded a mean Dbh at 12 months of 4.0 cm for the hardened treatment and 4.2 cm for the normally irrigated treatment.

Stocking showed no significant differences at 12 months for the high productivity trial (D01b) but BA was significantly different for the factors 1) residue management (SM) (p = 0.05) and 2) hardening (p = 0.02). At 12 months the nursery hardened (H) treatment recorded a mean Dbh = 2.1 $m^2\ ha^{-1}$ and non-hardened = 2.4 $m^2\ ha^{-1}$. All morphological measures at 12 months indicated that hardening of nursery stock might have been excessive in inhibiting growth without significantly improving stocking. Although residue treatments showed significant differences at the 95% confidence interval, mean values were very close for two of the three treatments with only spread slash significantly lower (Figure 4.34). The CV value at 12 months for BA = 10%.

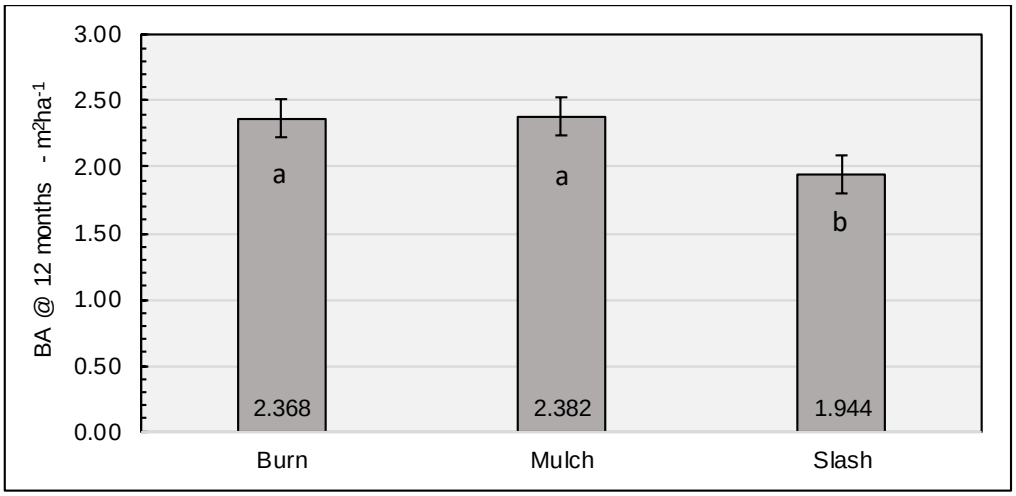

Figure 4.34: Trial D01b - Mean basal area (m^2ha^{-1}) at 12 months for residue treatment ($p < 0.05$; df = 6; se = 0.1100; lsd = 0.3805). Means with the same letter are not significantly different

One main factor and one interaction proved significant for crown diameter at 12 months 1) nursery hardening (H) (p = 0.073) and 2) residue management x nursery hardening (p = 0.026) (Figure 4.35) with the latter reported on further.

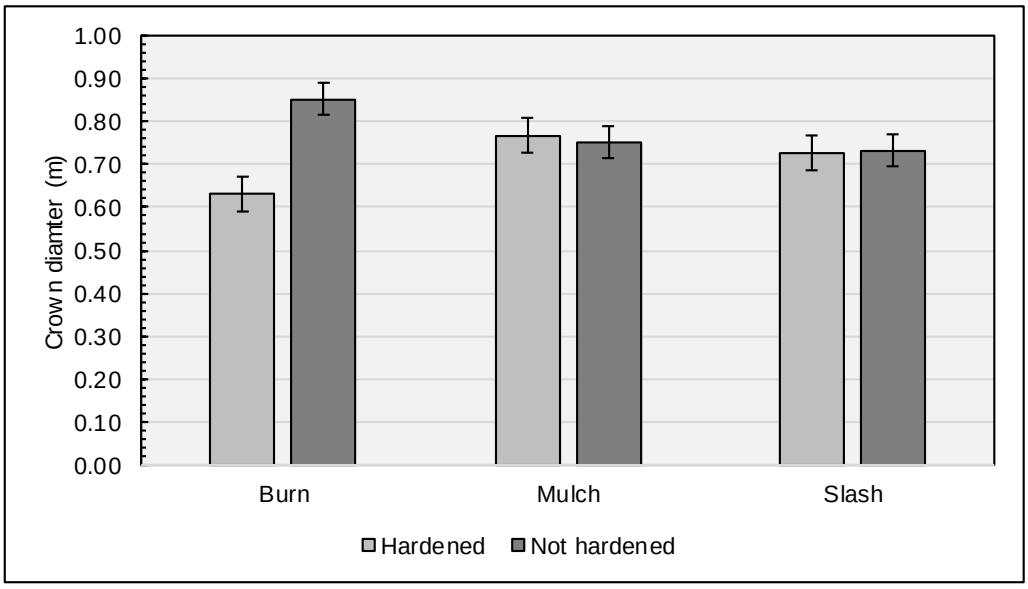

Figure 4.35: Trial D01b - Mean crown diameter (m) at 12 months for residue management x nursery hardening ($p < 0.05$; df = 8.57 se = 0.0824; lsd = 0.2656)

The best performing treatment for crown diameter at 12 months was residue burning combined with no nursery hardening (dia. = 0.9 m) with the poorest performer, burning combined with a nursery hardened treatment (dia = 0.6 m). Stomatal conductance and chlorophyll content index (CCI) showed no significant differences at the 95% confidence interval and were not reported further.

4.13.1. FINAL ROTATION MEASUREMENTS – HIGH PRODUCTIVITY SITE (TRIAL D010) – *E. DUNNII*

Final measures for the high productivity trial site (D010) were assessed at 99 months and included height (m), Dbh (cm), Dbh_CV (%), stocking (Spha), BA ($m^2 ha^{-1}$) and volume ($m^3 ha^{-1}$) as each underpins the primary economic drivers of short rotation eucalypt plantations, survival, growth and uniformity. For each of these three factors, a morphological surrogate exists. For survival, stocking correlates well, whilst basal area and volume describe tree growth. The best indicator of stand uniformity is the coefficient of variation of Dbh (Dbh_CV), with height an accurate descriptor of site quality, reported as site index at a specific reference age (SI_8 - site index at 8 years). To streamline reporting of results, only those main effects or interactions where the *F*-prob values were significant at the 95% confidence interval were discussed and in certain circumstances at the 90% confidence interval if relevant for a certain trial (Table 4.26).

At 98 months the factors 1) insecticide (I) ($p = 0.076$), 2) root plug volume (RPV) x nursery hardening ($p = 0.021$) and 3) residue management x insecticide ($p = 0.059$) were significantly different for height. Mean height for root plug volume x nursery hardening revealed the large plug volume (105 cm^3), not exposed to nursery hardening performed best at 19.8 m (Figure 4.36). The second highest mean height was a standard plug volume (60 cm^3) that had been hardened (19.6 m). The CV for height at 99 months = 5%, displayed a high degree of precision around mean height. Although statistically significant in terms of explaining variation within height, the difference between plug volume (RPV) and nursery hardening was only 20 cm. The impact of plug volume and hardening remained significant for mean height at 48 months ($p = 0.011$) for the same treatment combination but of little practical application. Plug volume and nursery hardening are nursery practices that play a major early response role up to 12 months but not major differences in final mean height gain.

Figure 4.36: Trial D010: Mean height (m) at 99 months for RPV x nursery hardening treatment combination ($p < 0.05$; df = 63; se = 0.1912; lsd = 0.5404)

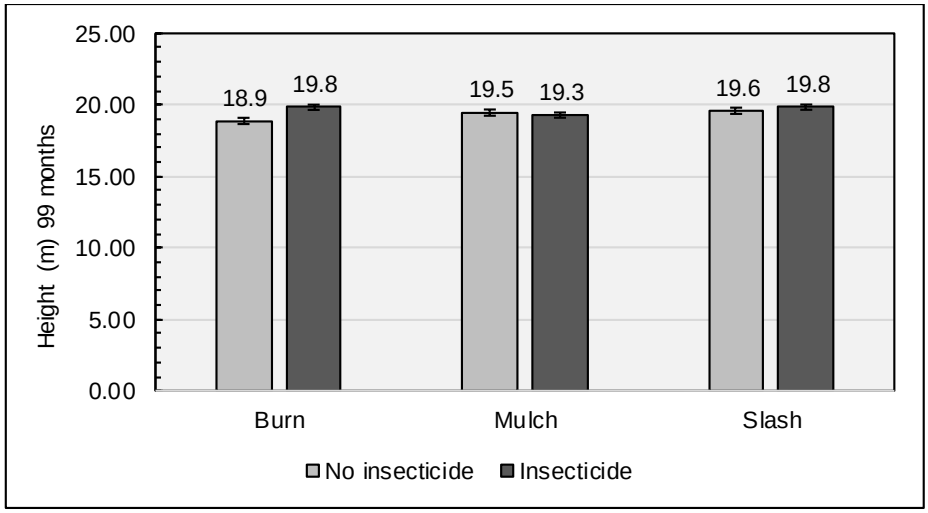

Figure 4.37: Trial D010: Mean height (m) at 99 months for residue management x insecticide treatment combination ($p < 0.05$; df = 0.21; se = 0.3748; lsd = 1.1948)

Residue management x Insecticide combination (Figure 4.37) showed significant differences for mean height at 99 months (p = 0.59) with the best mean height for two treatment combinations, 1) spread residue x insecticide application (19.8 m) and 2) burn x insecticide application (19.8 m). The worst performing mean height treatment was nearly a 1 m shorter for a burn x no insecticide combination (18.9 m). Hence residue treatment, not significant as a main effect on height at 99 months, (p = 0.709) played a lesser role as opposed to the early application of insecticide.

Dbh at 99 months showed residue management x root plug volume (p = 0.017) to be a significant interaction with the highest mean Dbh = 14.7 cm for spread residue x large plug volume (105 cm^3). The lowest mean Dbh = 13.9 m for mulch x large plug volume (105 cm^3)

and spread residue x standard plug volume (60 cm^3) (Figure 4.38). Residue management and RPV became less distinct in their impact on Dbh by full rotation. The CV for Dbh at 99 months = 6%, displayed a high degree of precision around mean Dbh whilst both the standard error and lsd scores were low, all indicating that Dbh within a given treatment was fairly uniform and stable at rotation end.

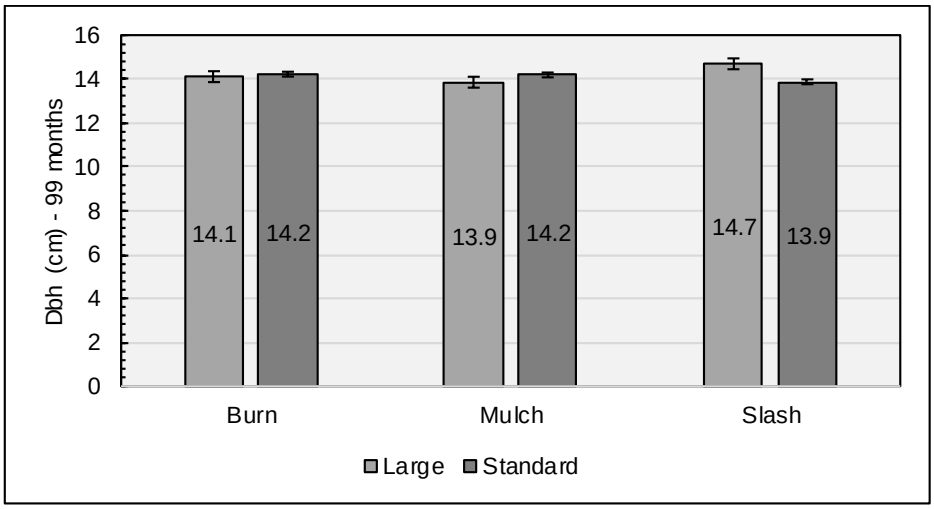

Figure 4.38: Trial D010, Mean Dbh (cm) at 99 months – Residue management x RPV interaction ($p < 0.05$; d.f = 6; se = 0.2839; lsd = 0.8843)

As a measure of stand uniformity, the coefficient of variation for Dbh (Dbh_CV) proved to be strongly significant (p = 0.01) for a combination of RPV x Hardening. The lowest CV score, indicator of Dbh uniformity, was recorded for nursery hardening x standard plug (60 cm^3) = 21% (Figure 4.39). In all cases, CV values were greater than 20% indicating that the spread of Dbh values were not uniform amongst treatments at final rotation.

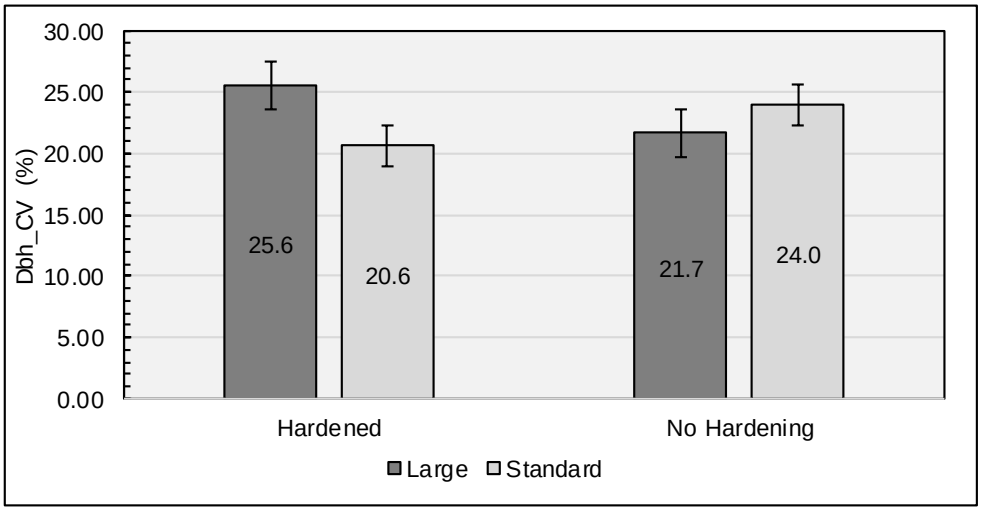

Figure 4.39: Trial D010 - Mean Dbh_CV (%) at 99 months for RPV x nursery hardening treatment ($p < 0.05$; df = 63; se = 1.359; lsd = 3.841)

Stocking (Spha) differences for Trial D010 at 98 months was significant ($p = 0.065$) for RPV x hardening as reported for height, Dbh and Dbh_CV, and thus an important treatment combination. The highest stocking level recorded (Figure 4.40) was for a nursery hardened x large plug combination at 1605 Spha. The lowest score at 1543 Spha was recorded for two diametrically different treatments, namely 1) nursery hardened x standard plug volume (60 cm^3) and 2) not hardened x large plug volume (105 cm^3). The consistent appearance of plug volume and nursery hardening did highlight that plug volumes responded to nursery conditioning through to final rotation in terms of height, Dbh, Dbh_CV and stocking.

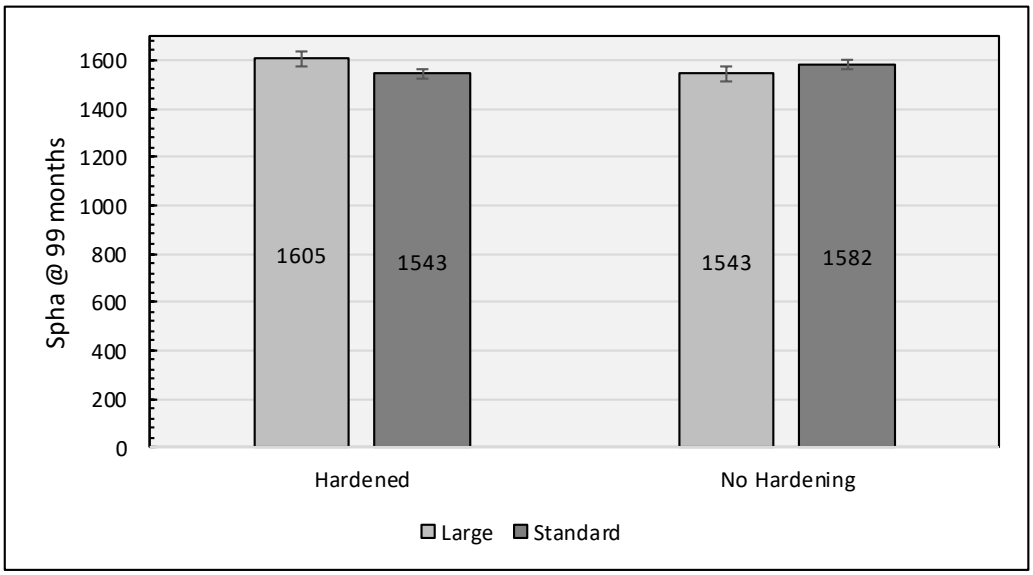

Figure 4.40: Trial D010 - Mean stocking (Spha) at 99 months for RPV x nursery hardening treatment ($p < 0.05$; df = 63; se = 26.7; lsd = 75.6)

Final volume (m^3 ha^{-1}) showed significant differences for 1) insecticide application (p = 0.062) and 2) residue management x RPV (p = 0.007) (Figure 4.41). Insecticide application resulted in a volume increase at 99 months of 11 m^3 ha^{-1} with insecticide treated plots = 194 m^3 ha^{-1} and untreated plots = 183 m^3 ha^{-1}. The factors residue management x RPV (p = 0.07) showed significant differences in mean final volume with spread residue x large plug volume = 212 m^3 ha^{-1}. All further volumes, ranked in order, were fairy clustered (Figure 4.41) with the lowest volume = 176 m^3 ha^{-1} for spread residue x standard plug volume, a decrease of 36 m^3 ha^{-1}.

Basal area showed significant differences for the same factors; namely, 1) insecticide (p = 0.071) and 2) residue management x RPV (p = 0.031).

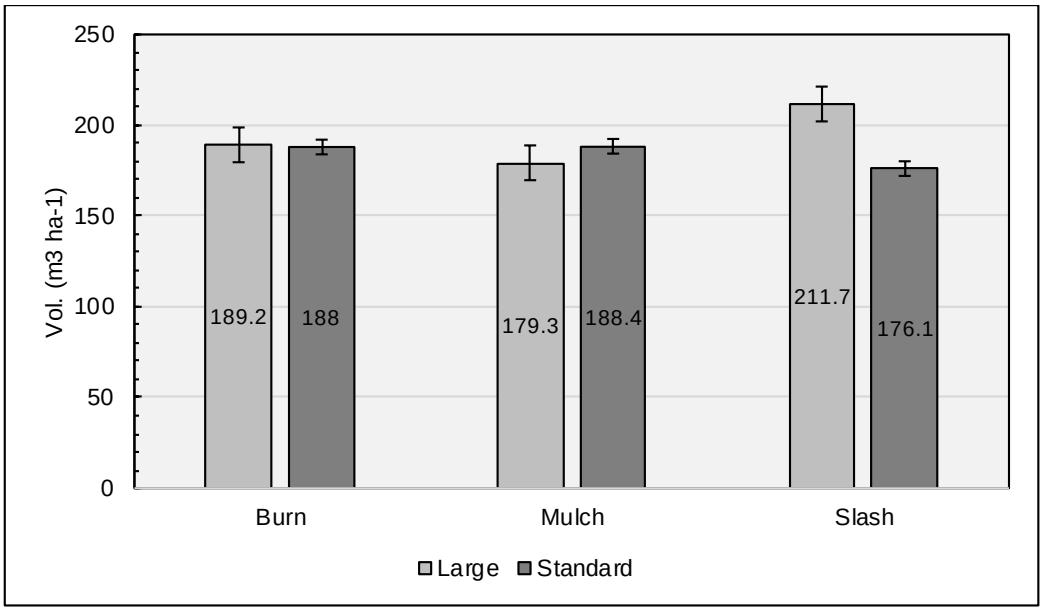

Figure 4.41: Trial D010 - Mean volume (m^3 ha^{-1}) at 99 months for residue management x RPV treatment ($p < 0.05$; df = 8.98; se = 11.81; lsd = 37.79)

Table 4.26: Summary of analysis of variance showing *F-prob* values for rotation-end for the *E. dunnii* trial series (Significance at $p < 0.05$ is shaded and in bold, with $p < 0.10$ shaded. Note: Plant size (PS) = Root plug volume (RPV); SM = residue management

Source of variation	df	D010						E013					
		Ht (m)	Dbh (cm)	Dbh_CV (%)	Stocking (sph)	BA (m^2 ha^{-1})	Vol (m^3 ha^{-1})	Ht (m)	Dbh (cm)	Dbh_CV (%)	Stocking (sph)	BA (m^2 ha^{-1})	Vol (m^3 ha^{-1})
Rep	3												
Slash management (SM)	2	0.709	0.756	0.487	0.609	0.916	0.807	0.591	0.273	0.087	0.082	0.84	0.914
Residual	6												
Plant size (PS)	1	0.811	0.461	0.339	0.667	0.208	0.119	0.078	0.135	**0.02**	0.587	0.177	0.321
Hardening (H)	1	0.476	0.637	0.84	0.667	0.882	0.825	0.717	0.716	0.955	0.786	0.98	0.943
Insecticide (I)	1	0.076	0.461	0.892	0.199	0.071	0.062	0.298	0.432	0.749	0.786	0.447	0.353
SM.PS	2	0.214	**0.017**	0.689	0.648	**0.031**	**0.007**	0.978	0.892	0.769	**0.041**	0.502	0.753
SM.H	2	0.962	0.820	0.304	0.940	0.996	0.938	0.759	0.924	0.636	**0.009**	0.101	0.177
PS.H	1	**0.021**	**0.009**	**0.01**	0.065	0.631	0.745	0.956	0.557	0.129	0.416	0.146	0.081
SM.I	2	0.059	0.345	0.235	0.648	0.816	0.662	0.409	0.313	0.39	0.704	0.827	0.853
PS.I	1	0.695	0.620	0.968	0.316	0.706	0.859	0.965	0.376	0.957	0.061	0.701	0.961
H.I	1	0.299	0.167	0.054	0.886	0.342	0.641	0.870	0.986	0.106	0.587	0.477	0.207
SM.PS.H	2	0.537	0.872	0.13	0.288	0.613	0.475	0.083	0.937	0.209	0.186	0.655	0.913
SM.PS.I	2	0.674	0.494	0.261	0.159	0.333	0.229	0.229	0.738	0.178	0.507	0.658	0.863
SM.H.I	2	0.540	0.528	0.562	0.979	0.500	0.409	0.701	0.498	0.932	0.454	0.234	0.349
PS.H.I	1	0.444	0.072	0.112	0.886	0.103	0.207	0.919	0.600	0.761	0.28	0.846	0.939
SM.PS.H.I	2	0.643	0.435	0.389	0.675	0.657	0.799	0.788	0.747	0.838	0.63	0.621	0.611
Residual	63												
Total	95												
Summary Statistics													
Grand mean		19.5	14.2	22.9	1568	25.9	188.8	19.4	13.8	26.0	1528	24.3	177.5
Standard error of differences of means (units)		0.66	0.58	4.71	92.6	1.98	20.30	0.99	0.77	6.38	98.0	2.63	26.69
Coefficient of variation (units) (%)		4.8	5.8	29.0	8.4	10.9	15.2	7.2	7.9	34.6	9.1	15.3	21.3

4.13.2. FINAL ROTATION MEASUREMENTS – MEDIUM PRODUCTIVITY SITE (TRIAL E013) - *E. DUNNII*

Measures for the medium productivity site (Trial E013) assessed at 99 months included height (m), Dbh (cm), Dbh_CV (%), stocking (spha), BA (m^2 ha^{-1}) and volume (m^3 ha^{-1}). To streamline reporting, only main effects or interactions where the *F*-prob values were significant at 90% or 95% confidence intervals were reported (Table 4.26).

At 99 months, 1) plug volume (PS = RPV) (p = 0.078) and 2) slash management x RPV x hardening (H) (p = 0.083) were significant at the 10% level for height with the latter reported on briefly below. Mean height at 99 months was tallest for spread residue x large plug volume x nursery hardening (mean height = 20.4 m) (Figure 4.42). The shortest mean height was the combination of mulch x standard plug volume x not nursery hardened (mean height = 18.5 m), a nearly 2.0 m difference (Figure 4.42). The CV value = 7% indicated a low level of dispersion around mean height.

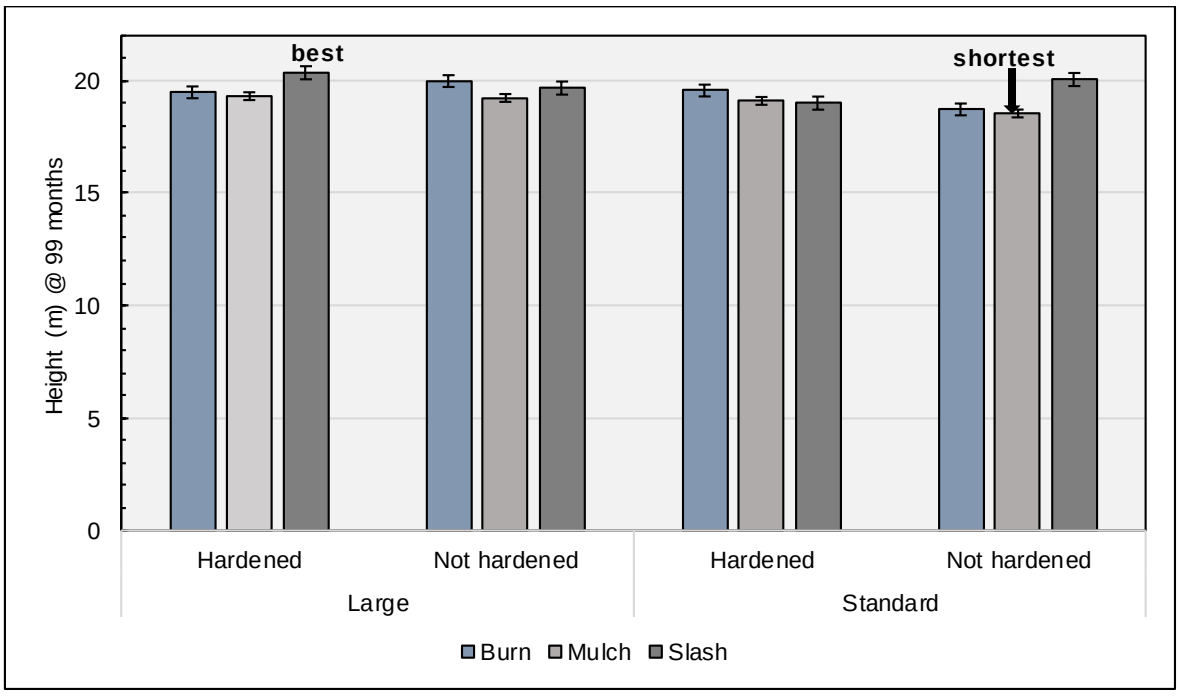

Figure 4.42: Trial E013: Mean height (m) at 99 months for residue management x RPV x hardening combination (p < 0.10; df = 18.20; se = 0.642; lsd = 1.906)

There were no significant mean Dbh differences measured at 99 months for any factors. At the residue management level the following mean Dbh values were recorded; burn = 11.6 cm, mulch = 11.5 cm and spread residue = 11.8 cm. In terms of Dbh, the role of the factors root plug volume, insecticide application and residue management had become less distinct after 48 months. The CV for Dbh at 99 months of 8% showed a high degree of precision

around mean Dbh with low standard error and lsd scores all indicating Dbh to be uniform.

Stocking for Trial E013 at 99 months was significant for the following treatments:

1. Residue management x RPV (p = 0.041).
2. Residue management x nursery hardening (H) (p = 0.009).

The interaction of residue management x RPV (p = 0.041) was significant at the 5% level (Figure 4.43). Burn treatments (97% survival) produced the highest stocking with the large plug = 1609 Spha and the standard plug = 1620 Spha. Importantly, residue management continued to play a dominant role with the lowest stocking for spread residue combined with the large plug = 1493 Spha, and spread residue x standard plug = 1377 Spha.

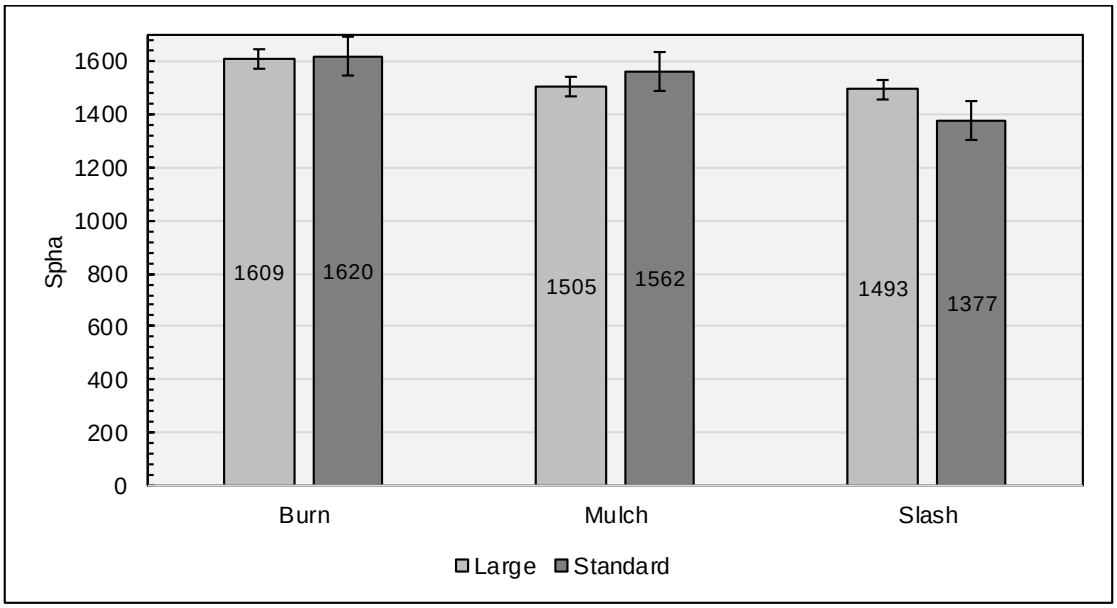

Figure 4.43: Trial E013 - Mean stocking (Spha) at 99 months for residue management (SM) x RPV (PS), (p < 0.05; se = 51.7; lsd = 163.1)

The interaction of the factors residue management x hardening (p = 0.009) was significant at the 1% level, the strongest measure recorded for explaining variance within stocking. Burn treatments were once again responsible for the highest stocking (97% survival), with nursery hardening also of importance. A combination of burning and nursery conditioning produced the highest stocking level at 1620 Spha, whereas burning combined with no nursery hardening = 1609 Spha. Spread residue combined with nursery hardening produced the second lowest stocking at 1493 Spha, with the lowest stocking for spread residue and seedlings not hardened in the nursery = 1377 Spha (Figure 4.44).

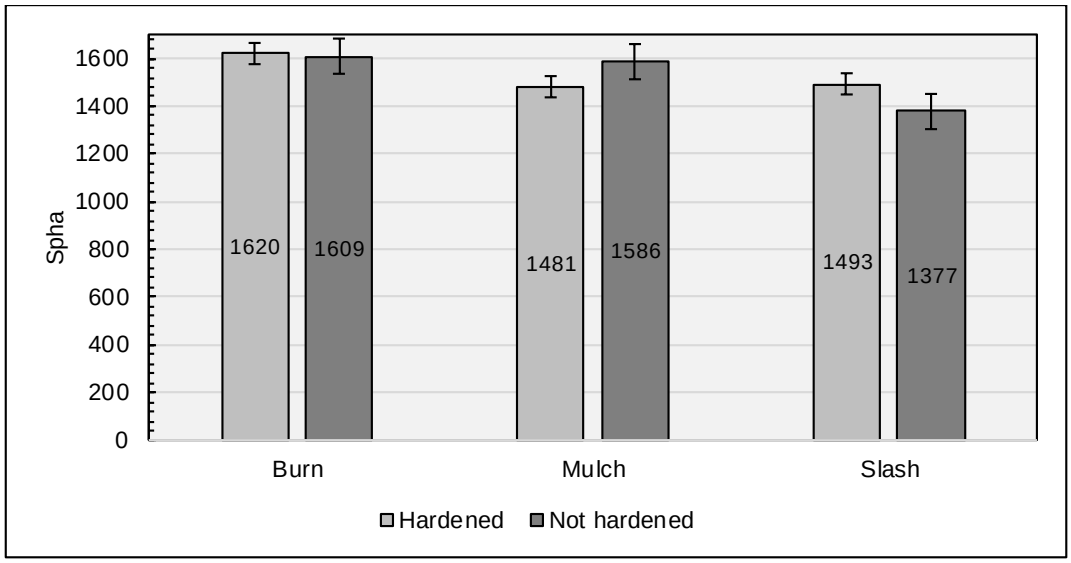

Figure 4.44: Trial E013 - Mean stocking (Spha) at 99 months for residue management (SM) x nursery hardening (H), ($p < 0.05$; se = 51.7; lsd = 163.1)

Basal area was not significant for any treatments at 99 months, whilst only RPV x nursey hardening ($p = 0.081$) showed significance for final volume (m^3 ha^{-1}) for Trial E013 at the 10% level (Figure 4.45). These results were inconsistent with the high productivity site (Trial D010) planted to *E. dunnii.* The best performing treatment was recorded for a large plug volume that had not been nursery hardened (188 ± 7.7 m^3 ha^{-1}) whilst the worst performing = 167 ± 7.7 m^3 ha^{-1} for a standard plug that was not nursery hardened. The grand mean for Trial E013 = 178 m^3 ha^{-1} whilst Trial D010 = 189 m^3 ha^{-1}. The CV value for volume for Trial E013 was a relatively high 21%.

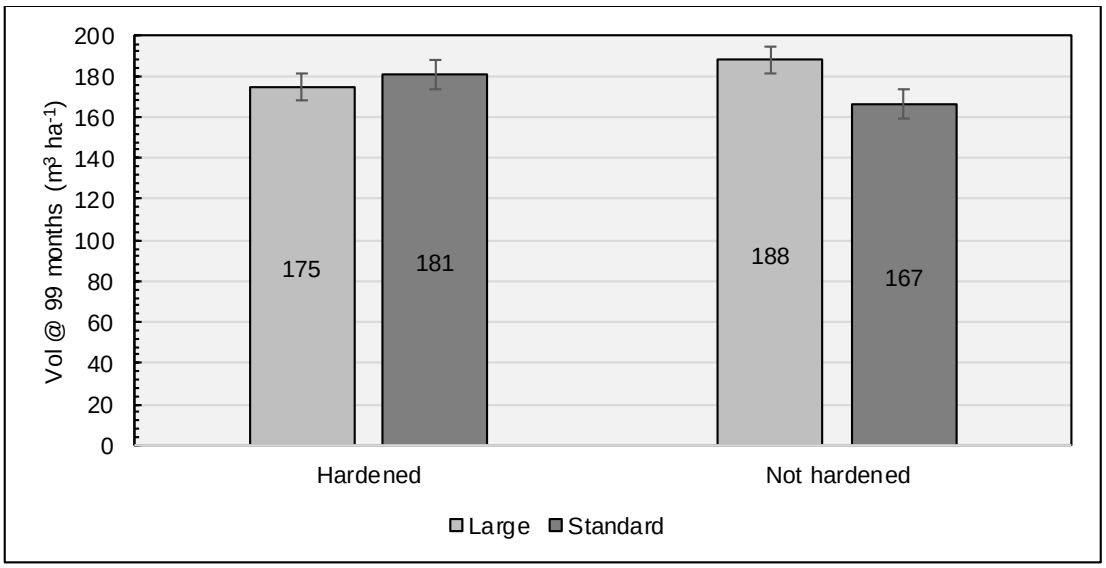

Figure 4.45: Trial E013 - Mean volume (m^3 ha^{-1}) at 99 months for residue management (SM) x RPV (PS) treatment ($p < 0.10$; df = 63; se = 7.70; lsd = 21.77)

4.13.3. FINAL ROTATION MEASUREMENTS – MEDIUM PRODUCTIVITY SITE (TRIAL F026) – *E.GXN*

Measurements for the medium productivity site (Trial F026 - *E. gxn*) were assessed at 84 months and included height (m), Dbh (cm), Dbh_CV (%), stocking (spha), BA (m^2 ha^{-1}) and volume (m^3 ha^{-1}). Only main effects or treatment interactions where *F*-prob values were significant at 95% confidence intervals were reported and where applicable at the 90% confidence interval (Table 4.27).

Height showed no significant differences for any treatment and grand mean height = 19.8 m. Mean Dbh was significant for 1) RPV x insecticide application ($p = 0.089$) ($p < 0.10$) and 2) RPV x hardening x insecticide ($p = 0.055$). The latter three-way interaction was included as the most comprehensive explanation of response (Figure 4.46).

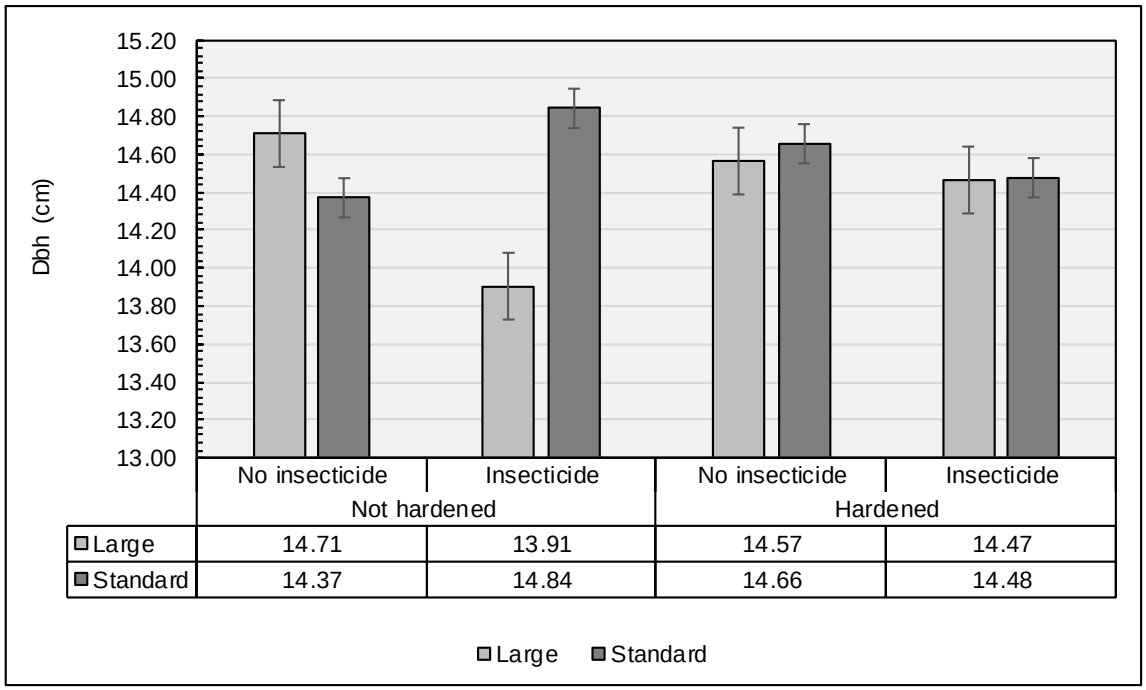

Figure 4.46: Trial F026 - Mean Dbh (cm) at 84 months for RPV x hardening x insecticide treatment ($p < 0.10$; se = 0.2450; lsd = 0.6923)

The highest mean Dbh at 84 months (14.8 cm) (Figure 4.46) was recorded for a standard plug volume x no nursery hardening x insecticide combination. The lowest mean Dbh = 13.9 cm, for a large plug volume x no hardening x insecticide. For the factor interaction RPV x insecticide (excluding hardening), the standard plug treated with an insecticide produced a mean Dbh = 14.7 cm, whilst the large plug treated with insecticide, the lowest Dbh = 14.2 cm. For this trial, it could be deduced that plug volume and insecticide application were of greater importance than hardening (Figure 4.46). All statistical factors pointed to very little

treatment variation around the mean Dbh at rotation end. As a measure of stand uniformity, the coefficient of variation for Dbh (Dbh_CV) proved to be significant (p = 0.097) for residue management x RPV x hardening. The lowest Dbh_CV (13%), and hence most uniform, was for the treatment combination of a standard plug x burning x insecticide application. The least uniform Dbh (19%) was for mulching x standard plug (60 cm^3) x no insecticide application. Overall CV for DbH_CV (43%) showed a high degree of dispersion of Dbh measures around the mean for the site and may be attributed to poor stocking (mean = 1256 Spha) where gaps in the compartment reduce immediate neighbour competition around surviving trees causing greater Dbh variation.

Trial F026 sustained windstorm damage at 18 months that affected final stocking (Spha) at 84 months; however, differences in stocking were still significant for the following factors: 1. Root plug volume (p = 0.01). 2. RPV x hardening (H) x insecticide (I) (p = 0.004). The large plug (105 cm^3) showed better mean stocking for site F026 (*E. gxn*) at 1316 Spha (79% survival) whilst the standard plug (60 cm^3) = 1196 Spha (72% survival). Nursery hardening affected stocking levels with treatments not hardened = 1296 Spha and hardened plants = 1215 Spha. The application of an insecticide had beneficial effects with insecticide treatments = 1300 Spha and untreated plots = 1211 Spha. The interaction of plug volume, nursery hardening and application of insecticide showed significant benefits to final stocking (p < 0.05). The best stocking level of 1389 Spha was achieved for a large plug volume x insecticide application x nursery hardened, with the worst stocking (1096 Spha) for a standard plug x nursery hardening x insecticide. (Figure 4.47).

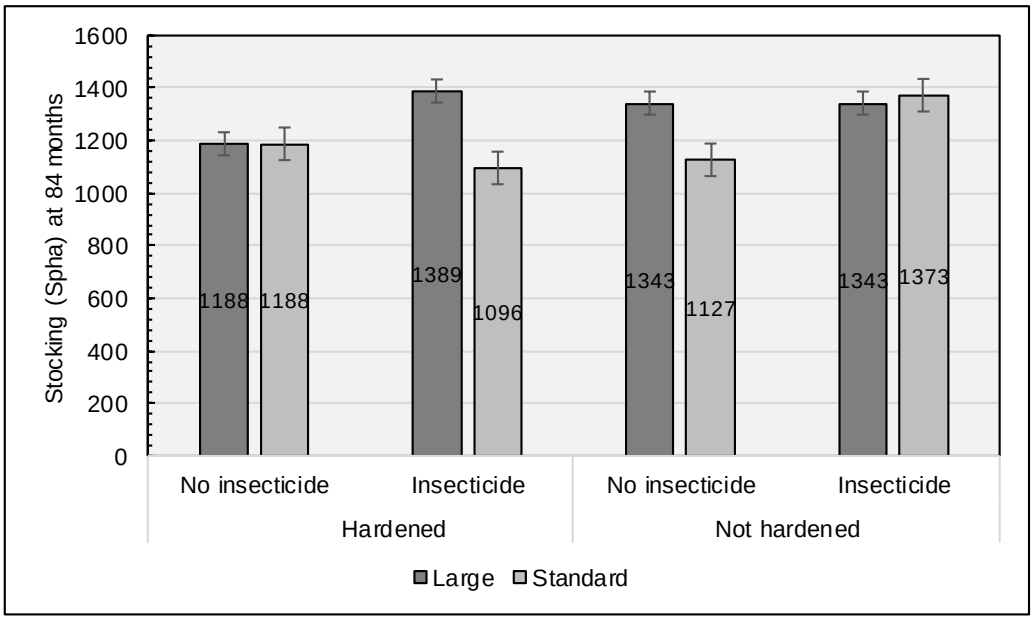

Figure 4.47: Trial F026 – Mean stocking (Spha) at 84 months for RPV x hardening x insecticide, (p < 0.05; df = 63; se = 63.7; lsd = 180)

Basal area was significant for two silvicultural treatments:

1. Root plug volume (RPV indicated as PS in tables) ($p = 0.04$).
2. Hardening (H) ($p = 0.073$).

At 84 months, plug volume showed a significant difference for basal area with the large plug (105 cm^3) = 21.8 m^2 ha^{-1} and the standard plug (60 cm^3) = 20.3 m^2 ha^{-1}. Nursery conditioning of planting stock showed that hardening through water deprivation decreased basal area means (20.4 m^2 ha^{-1}) whilst planting stock not subject to drought hardening showed a greater basal area = 21.7 m^2 ha^{-1}. The overall CV value for basal area at 84 months = 17%.

Volume at 48 months (m^3 ha^{-1}) was significant for the following silvicultural treatments:

1. Root plug volume ($p = 0.026$).
2. Hardening (H) ($p = 0.053$).
3. Residue management x RPV x nursery hardening (SM x PS x H) ($p = 0.075$).
4. Residue management x nursery hardening x insecticide ($p = 0.028$).
5. RPV x hardening x Insecticide ($p = 0.059$).

At 84 months (final measure) no silviculture treatment was significant at the 5 or 10% level (Table 4.27) with plug volume and nursery hardening in excess of 10% confidence level. The grand trial mean volume = 147.5 m^3 ha^{-1}. Plug volume showed no significant differences ($p = 0.11$), with the large plug volume (105 cm^3) = 152 m^3 ha^{-1} and standard plug volume (60 cm^3) = 143 m^3 ha^{-1}.

4.13.4. FINAL ROTATION MEASUREMENTS – HIGH PRODUCTIVITY SITE (TRIAL D01B)

At 87 months, mean height showed significant differences for a RPV x insecticide combination ($p = 0.031$). The tallest mean height recorded = 22.7 m for a standard plug (60 cm^3) x insecticide treatment, with the lowest mean = 21.9 m for two distinctly different treatments, 1) standard plug x no insecticide and 2) large plug (105 cm^3) x insecticide (Figure 4.48).

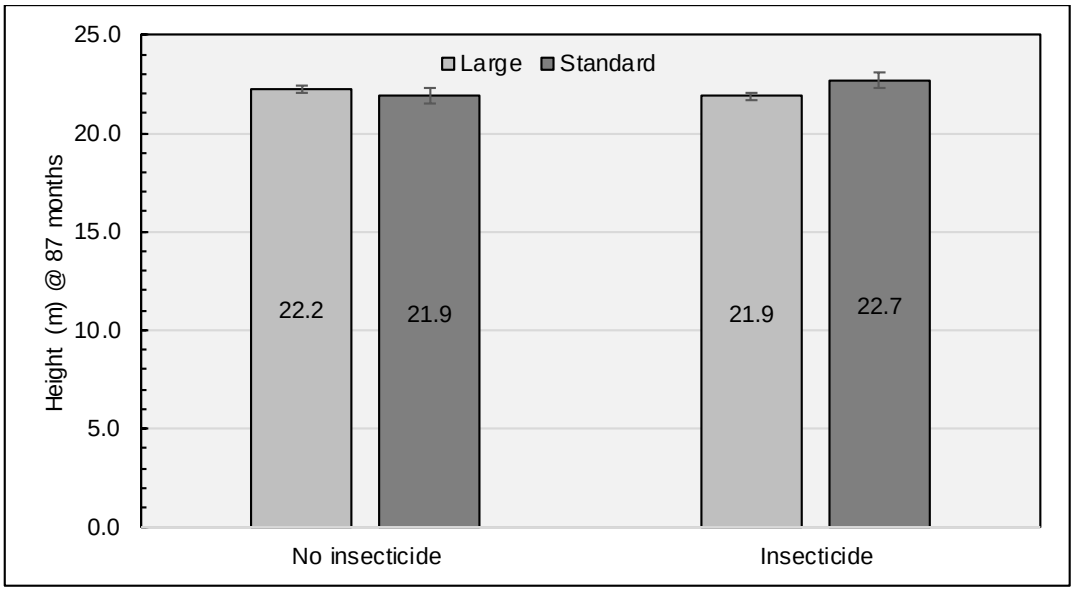

Figure 4.48: Trial D01b - Mean height (m) at 87 months for RPV x Insecticide treatment ($p < 0.05$; df = 63; se = 0.263; lsd = 0.742)

Mean Dbh was significant for RPV x nursery hardening ($p = 0.024$) at the 5% level (Figure 4.49). Best performing silviculture treatments were for a standard plug that had been hardened in the nursery through irrigation regulation (Dbh = 14.7 cm), whereas the poorest performing treatment was a standard plug not exposed to nursery water hardening (Dbh = 14.0 cm). A recurring pattern of plug volume and associated hardening was apparent when comparing height and Dbh performance. The CV value for Dbh = 9% and reflected a low degree of dispersion of Dbh around the means and little treatment variation.

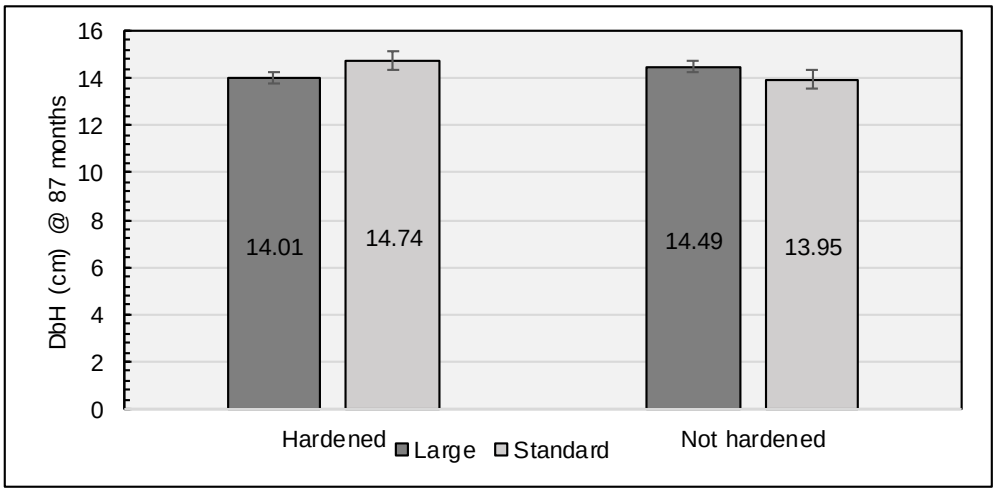

Figure 4.49: Trial D01b - Mean Dbh (cm) at 87 months for RPV x hardening ($p < 0.05$; df = 63; se = 0.273; lsd = 0.771)

As a measure of stand uniformity, the coefficient of variation for Dbh (Dbh_CV) proved to be significant for two differing silviculture factors at the 95% confidence level (Table 4.27), 1. Residue management (SM) ($p = 0.013$). 2. Residue management x RPV ($p = 0.014$).

For residue management, DbH_CV for treatments were; burning = 21%, mulching = 22% and spread residue = 27%. These were all reasonably high levels of dispersion around the mean and pointed to variance in Dbh. The residue management x RPV combination (p = 0.014) (Figure 4.50) showed that burn treatments planted to a standard 60 cm^3 plug produced the lowest spread of Dbh measures (18%) whereas the worst mean, Dbh_CV = 28%, occurred where a standard plug was planted into spread residues. These findings supported the assumption that unevenly spread residues can have a negative impact on the uniformity of a stand.

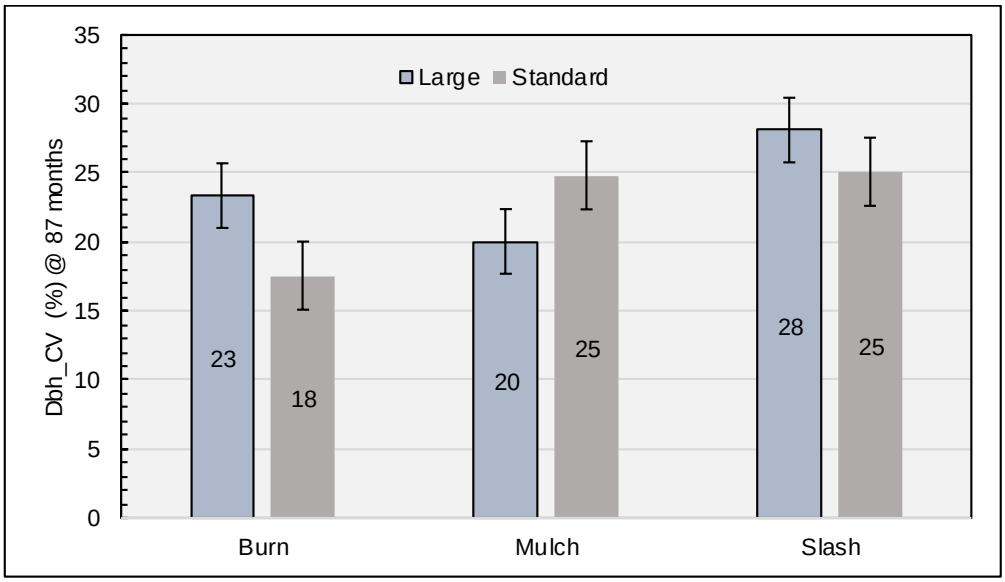

Figure 4.50: Trial D01b - Mean Dbh_CV (%) at 87 months for residue management x RPV, (p < 0.05; df = 63; se = 0.273; lsd = 0.771)

Trial D01b showed no significant differences in mean stocking (spha) at the 5% level at 87 months with the greatest difference being recorded among a combination of residue management and hardening treatments (p = 0.104). The best stocking was recorded for hardened nursery plants established on a burnt site (1586 Spha) with the lowest stocking (1458 Spha) measured where unhardened nursery stock was planted into mulch or spread residues. The lower stocking may have been due to insect attack by the larvae of chafer beetles, although this usually affects burn treatments and may result from the impact of heat or cold at time of planting when spread residues are most unevenly distributed.

Mean basal area (m^2 ha^{-1}) was significant for RPV x hardening (p = 0.013) at 87 months. The highest mean BA = 27.9 m^2 ha^{-1} for a standard plug hardened in the nursery, whilst the lowest BA = 24.1 m^2 ha^{-1} for an unhardened plug with the same plug dimensions (Figure 4.51). This finding conflicts with the previous *E. gxn* experiment site (Trial F026) where

hardening decreased basal area means (20.4 m^2 ha^{-1}) whereas planting stock not subject to drought hardening showed a greater basal area of 21.7 m^2 ha^{-1}.

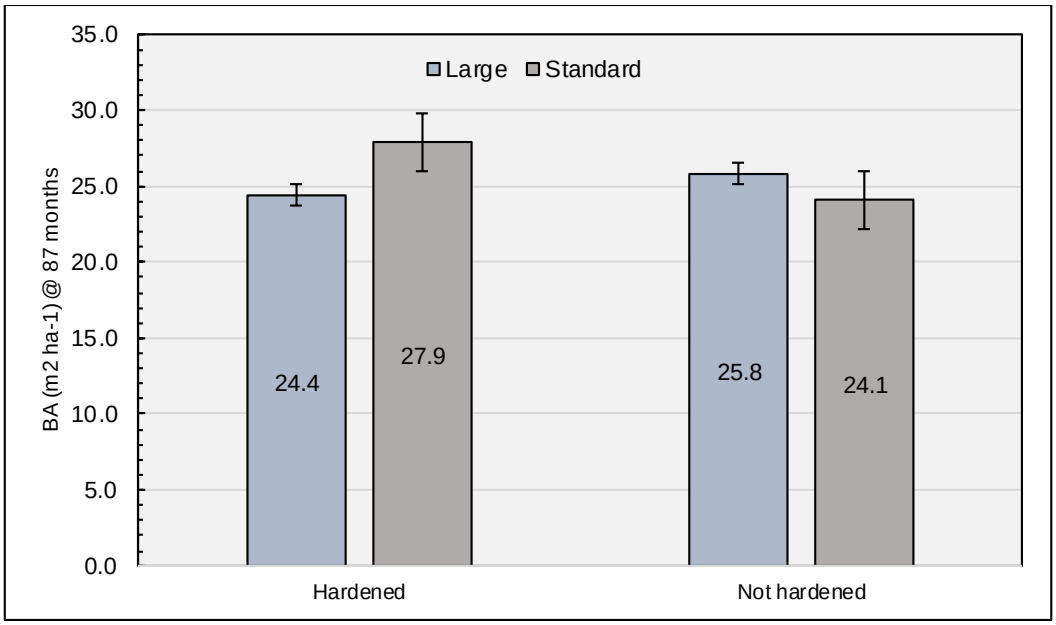

Figure 4.51: Trial D01b – Mean BA (m^2 ha^{-1}) at 87 months for RPV x hardening, ($p < 0.05$; df = 63; se = 1.013; lsd = 2.8631)

Mean stand volume was significant for RPV x hardening treatment ($p = 0.009$) at 87 months (Figure 4.52). The highest mean volume = 243 m^3 ha^{-1} for a standard plug x hardened in the nursery, whilst the lowest volume = 185 m^3 ha^{-1} for an unhardened plug with the same plug dimensions (Figure 4.52). The difference of 58 m^3 ha^{-1} for the interactions is a revelation as hardening as a single factor was not significant ($p = 0.136$).

The synergistic effect of combining the plug volume with hardening in the nursery produced a major volume difference, quite contrary to the hypothesis whereby a large plug volume should outgrow its smaller counterpart. The best volume producing combination for the high productivity site (D01b) = standard plug volume x nursery hardening whilst for the medium productivity site (F026), where no significant differences were recorded (Table 4.27) = plug volume x nursery hardening x insecticide. In summary, a combination of plug volume x nursery hardening x insecticide remained an excellent overall recommendation, even more important than the residue management responses.

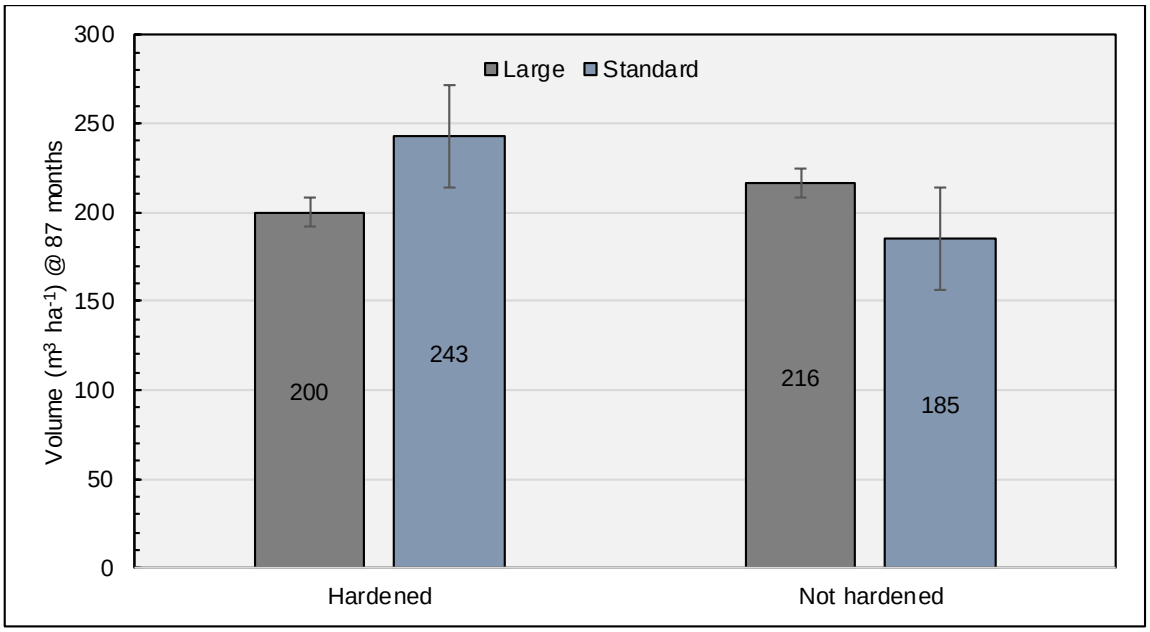

Figure 4.52: Trial D01b – Mean volume (m^3 ha^{-1}) at 87 months for RPV x hardening, ($p < 0.05$; df = 63; se = 13.69; lsd = 38.68)

Table 4.27: Summary of analysis of variance showing *F-prob* values for rotation-end for *the E. gxn* trials (Significance at $p < 0.05$ in bold). Note: Plant size (PS) = Root plug volume (RPV); SM = residue management

Source of variation	df	F026						D01b					
		Ht (m)	Dbh (cm)	Dbh_CV (%)	Stock (sph)	BA (m^2 ha^{-1})	Vol (m^3 ha^{-1})	Ht (m)	Dbh (cm)	Dbh_CV (%)	Stock (sph)	BA (m^2 ha^{-1})	Vol (m^3 ha^{-1})
Rep	3												
Slash management (SM)	2	0.905	0.454	0.44	0.228	0.302	0.440	0.972	0.81	**0.013**	0.195	0.949	0.814
Residual	6												
Plant size (PS)	1	0.448	0.315	0.393	**0.01**	**0.04**	0.110	0.349	0.736	0.369	0.165	0.402	0.681
Hardening (H)	1	0.238	0.634	0.556	0.077	0.073	0.116	0.805	0.56	0.052	0.816	0.239	0.136
Insecticide (I)	1	0.419	0.381	0.8	0.053	0.17	0.423	0.425	0.681	0.389	0.816	0.534	0.411
SM.PS	2	0.614	0.758	0.692	0.87	0.818	0.612	0.898	0.927	**0.014**	0.324	0.219	0.148
SM.H	2	0.415	0.239	0.779	0.347	0.682	0.811	0.207	0.593	0.774	0.104	0.118	0.271
PS.H	1	0.397	0.477	0.238	0.551	0.804	0.406	0.455	**0.024**	0.154	0.816	**0.013**	**0.009**
SM.I	2	0.502	0.587	0.848	0.763	0.995	0.943	0.215	0.21	0.451	0.947	0.23	0.216
PS.I	1	0.102	0.089	0.105	0.798	0.322	0.167	**0.031**	0.106	0.143	0.816	0.138	0.167
H.I	1	0.123	0.938	0.961	0.444	0.365	0.211	0.215	0.283	0.508	0.642	0.46	0.377
SM.PS.H	2	0.236	0.142	0.097	0.95	0.556	0.446	0.481	0.46	0.938	0.804	0.307	0.309
SM.PS.I	2	0.996	0.583	0.596	0.144	0.19	0.187	0.948	0.577	0.572	0.141	0.152	0.353
SM.H.I	2	0.613	0.364	0.753	0.858	0.446	0.228	0.946	0.593	0.877	0.684	0.889	0.979
PS.H.I	1	0.993	0.055	0.612	**0.004**	0.063	0.242	0.212	0.467	0.852	0.642	0.619	0.365
SM.PS.H.I	2	0.56	0.74	0.794	0.383	0.379	0.340	0.763	0.755	0.392	0.422	0.393	0.395
Residual	63												
Total	95												
Summary Statistics													
Grand mean		19.8	14.5	16.4	1256	21.0	147.5	22.2	14.3	23.2	1505	25.6	211.1
Standard error of differences of means (units)		0.63	0.60	4.94	156.1	2.48	19.18	0.91	0.95	5.14	114.3	3.51	47.42
Coefficient of variation (units) (%)		4.5	5.9	42.9	17.6	16.7	18.4	5.8	9.3	31.4	10.7	19.4	31.8

4.14. ABSOLUTE AND RELATIVE VALUE SCORES

Data sets at 12 months and full trial rotation were large and only reported at the 5% level in terms of main and interactive effects, prior to expounding of absolute and relative growth differences. Basal area was selected as the parameter that could be most accurately calculated from 12 months through to full rotation and deemed of greater relevance than either Gld/Dbh or height. Main and interactive effects of significance at the 5% level were first tabularised (Table 4.26, Table 4.27, Table 4.28) at 12 months, and final rotation, prior to describing basal area in terms of absolute and relative growth differences.

Table 4.28: Summary ANOVA showing *F-prob* values for significant differences in tree size at 12 months. (Significance at 5%level)

Source of variation	*E. dunnii*						*E. grandis x E. nitens*					
	D010 (High)			E013 (Medium)			F026 (Medium)			D01b (High)		
	Ht (m)	Dbh (cm)	BA (m^2 ha^{-1})	Ht (m)	Dbh (cm)	BA (m^2 ha^{-1})	Ht (m)	Dbh (cm)	BA (m^2 ha^{-1})	Ht (m)	Dbh (cm)	BA (m^2 ha^{-1})
Slash mgt (SM)				0.006	0.008	0.009	0.02	0.013	0.014			0.05
Plant size (PS)				0.008	<.001	<.001	<.001	<.001	<.001			
Hardening (H)							0.047	0.021	0.005	0.01	0.029	0.02
SM.PS		0.008	0.028									
H.I								0.05				
Grand mean	4.4	4.4	2.6	3.6	3.5	1.7	2.7	4.2	2.06	2.3	4.1	2.23
Standard error of differences of means (units)	0.22	0.33	0.39	0.27	0.37	0.33	0.20	0.21	0.61	0.22	0.34	0.37
Coefficient of variation (units) (%)	7.2	10.8	21.6	10.6	14.8	27.0	10.5	7.1	17.4	13.3	11.9	23.6

At the 12-month measure, the following could be summarised for the significance of basal area for main effects and their interactions (Table 4.28):

1. Basal area was significant for residue management across three of the four trial sites, with burning recording the highest BA.
2. The two medium productivity trial sites (both genotypes) showed BA responded significantly at 12 months to plug volume, with the large plug volume superior.
3. The two *E gxn* trial sites responded significantly to nursery hardening in terms of BA whereas the *E. dunnii* trial sites did not.
4. Basal area responded significantly to the interaction of residue management x plug volume on only one site (D010), with the large plug in the burning treatment recording the highest value.

At final rotation, the following could be summarised for the significance (5% level) of BA for main effects and their interactions (Table 4. 29, Table 4.30):

1. Plug volume as a single factor was of little consequence in terms of basal area at full rotation for the *E. dunnii* sites but important for the medium productivity *E. gxn* site (large plug sizes were superior).
2. Nursery hardening (H) was not significant for BA in the *E. dunnii* trials but weakly significant for the medium productivity E*. gxn* trial site, with non-hardened plants superior.
3. Application of insecticide as a main effect was significant at the 10% level for BA on the high productivity *E. dunnii* site.
4. The interaction of residue management x root plug volume was significant for BA on the high productivity *E. dunnii* site (superior treatment = large plug volumes planted into spread slash).
5. The interaction of root plug volume x hardening was strongly significant for height and Dbh, but not significantly for BA on *E. dunnii* sites, but strongly significant for the high productivity *E. gxn* site (superior treatment = standard plug size, nursery hardened).
6. The interaction of root plug volume x nursery hardening x insecticide (PS x H x I) was significant for BA at the 10% confidence level for the medium productivity *E. gxn* trial site for the combination of a large root plug, not nursery hardened and planted with insecticide.
7. There were interactions between 1) residue management x RPV and 2) residue management x hardening with respect to stocking, but neither of these influenced BA or volume significantly.

Table 4.29: Summary ANOVA showing *F-prob* values at rotation-end for *E. dunnii* trial series (Significance at 5% level)

Source of variation	D010 (High)						E013 (Medium)					
	Ht (m)	Dbh (cm)	Dbh_CV (%)	Stocking (sph)	BA (m^2 ha^{-1})	Vol (m^3 ha^{-1})	Ht (m)	Dbh (cm)	Dbh_CV (%)	Stocking (sph)	BA (m^2 ha^{-1})	Vol (m^3 ha^{-1})
Plant size (PS)									**0.02**			
Insecticide (I)	0.076				0.071	0.062						
SM.PS		**0.017**			**0.031**	**0.007**				**0.041**		
SM.H										**0.009**		
PS.H	**0.021**	**0.009**	**0.01**	0.065								0.081
SM.I	0.059											
PS.I										0.061		
H.I			0.054									
SM.PS.H							0.083					
PS.H.I		0.072										
Grand mean	19.5	14.2	22.9	1568	25.9	188.8	19.4	13.8	26.0	1528	24.3	177.5
Standard error of differences of means (units)	0.66	0.58	4.71	92.6	1.98	20.30	0.99	0.77	6.38	98.0	2.63	26.69
Coefficient of variation (units) (%)	4.8	5.8	29.0	8.4	10.9	15.2	7.2	7.9	34.6	9.1	15.3	21.3

Table 4.30: Summary of analysis of variance showing *F-prob* values for rotation-end for *the E. gxn* trials (Significance at 5% level)

Source of variation	F026 (Medium)						D01b (High)					
	Ht (m)	Dbh (cm)	Dbh_CV (%)	Stock (sph)	BA (m^2 ha^{-1})	Vol (m^3 ha^{-1})	Ht (m)	Dbh (cm)	Dbh_CV (%)	Stock (sph)	BA (m^2 ha^{-1})	Vol (m^3 ha^{-1})
Slash management (SM)									**0.013**			
Plant size (PS)				**0.01**	**0.04**							
Hardening (H)				0.077	0.073				0.052			
Insecticide (I)				0.053								
SM.PS									**0.014**			
PS.H								**0.024**			**0.013**	**0.009**
PS.I		0.089					**0.031**					
PS.H.I		0.055		**0.004**	0.063							
Grand mean	19.8	14.5	16.4	1256	21.0	147.5	22.2	14.3	23.2	1505	25.6	211.1
Standard error of differences of means (units)	0.63	0.60	4.94	156.1	2.48	19.18	0.91	0.95	5.14	114.3	3.51	47.42
Coefficient of variation (units) (%)	4.5	5.9	42.9	17.6	16.7	18.4	5.8	9.3	31.4	10.7	19.4	31.8

The above bulleted points, for 12 months and full rotation, offered sufficient justification to discuss basal area (BA) in terms of absolute and relative values. Little (2014) refers to three factors of importance when comparing treatment impacts, the magnitude, timing and duration of response. Absolute differences reflect variations between two treatments whilst relative treatment differences is the difference between two treatments, divided by the

existing standard operational treatment over time. This is an effective tool for management comparative purposes where expressing differences in terms of a statistical significance are difficult to visualise in terms of practical operational gains. Absolute and relative values proved suitable to comparing differences between main silviculture treatments but cumbersome when applied to two or three way interactions. Where interactions were significant mean square values (Section 4.3) proved better suited in accounting for differences in mean BA.

4.14.1. HIGH PRODUCTIVITY SITE (TRIAL D010 – *E.DUNNII*): ABSOLUTE DIFFERENCES MEAN BASAL AREA

For the high productivity site (Figure 4.53a), mean basal area measured for the residue treatments, burning, spreading of residue (slash) and mulching showed weak Type 2 growth responses, with a fairly slow early growth phase affecting productivity towards full rotation. From 0 – 1150 Dap, burning showed the largest mean BA and this positive response remained through to full rotation, as opposed to Dbh, where slash had the largest mean Dbh from 1150 (≈ 3 years) through to 3011 Dap (figure not presented). Mulch and spread responded similarly with mulch showing the lowest BA from 5 years onwards. Plug volume (RPV) revealed that the large plug outperformed the standard plug from 0 – 3011 days after planting (DAP). In terms of absolute differences, RPV continued to have an impact on BA but the relative difference remained constant (Figure 4.53b).

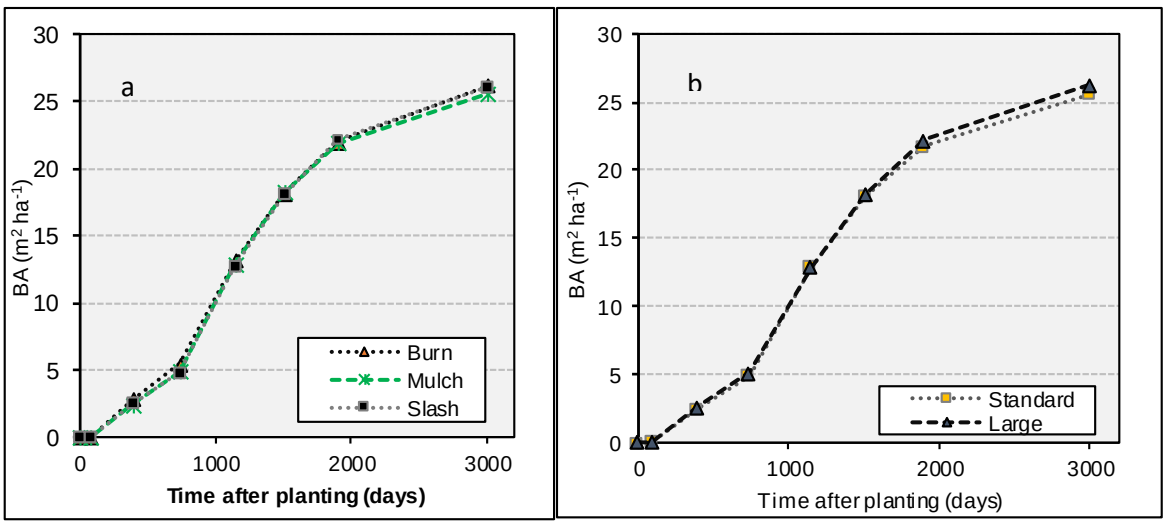

Figure 4.53: Trial D010: Residue management (a = left) and RPV (105 cm³ vs standard 60 cm³) (b = right) plots for basal area (m² ha⁻¹) from 0 – 3011 (DAP)

Where no nursery hardening was applied, BA scored consistently higher (Figure 4.54a). This may have been due to excessive water deprivation in the nursery resulting in the

dieback of root volume. At 5 years (1901 DAP), the hardened and unhardened treatments started to diverge slightly. Although hardening in the nursery does have recorded early benefits, excessive hardening negatively affected BA in this trial. The application of an insecticide drench showed greater mean BA benefits from 86 - 3011 DAP with a final BA gain for insecticide treatment = 1.05 m^2 over the untreated plots (Figure 4.54b). As a main silviculture treatment, insecticide applications benefited BA through full rotation.

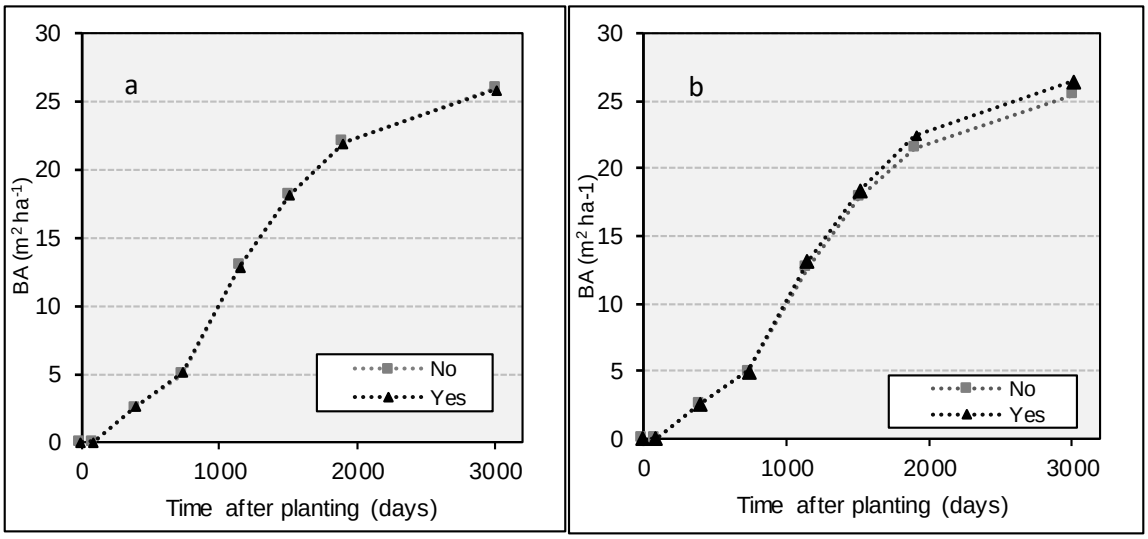

Figure 4.54: Trial D010: Application of nursery hardening (a = left) and insecticide (a.i. alpha cypermethrin) (b= right) plots for basal area (m^2 ha^{-1}) from 0 – 3011 DAP

Absolute differences are presented in the sections that follow for each trial (Figures 4.55, 4.59, 4.63 and 4.67). The reader is reminded that a negative value for the absolute differences in these four graphs are indicative of the superiority of using hardening, insecticide application, large plug volumes and no-burning treatments. The interpretation is the same for the relative differences in Figures 4.56; 4.60; 4.64 and 4.68).

Absolute differences showed that from 0 – 734 DAP, burning produced a higher mean BA than slash retention (Figure 4.55) = 0.54 m^2 ha^{-1}. Thereafter, this would decline to a slight negative difference between burning and residue retained (slash) treatments (-0.05 m^2 ha^{-1}) but rebound to a positive gain in favour of burning of 0.58 m^2 ha^{-1} at final rotation. Absolute differences between burning and mulch showed a gain in favour of burning of 0.65 m^2 ha^{-1} at 2 years, declining as for the burning – slash difference, but only becoming negative at 5 years in favour of mulch. By final rotation at 3011 DAP; there would be a recovery in BA in favour of burning, albeit slight.

RPV showed a long-term gain for the large plug. At 1150 DAP, this difference in favour of the large plug would disappear before reoccurring and growing to 0.73 m^2 ha^{-1} at 3011 DAP

(full rotation) (Figure 4.55). Hardening showed no benefits up to 2 years (734 DAP) and thereafter the absolute differences of not hardening increased very little to full rotation. Insecticide application showed low absolute differences initially, until 2 years, where after the impact of insecticide grew to 1.05 m^2 ha^{-1} by 3011 DAP (full rotation at 8 years).

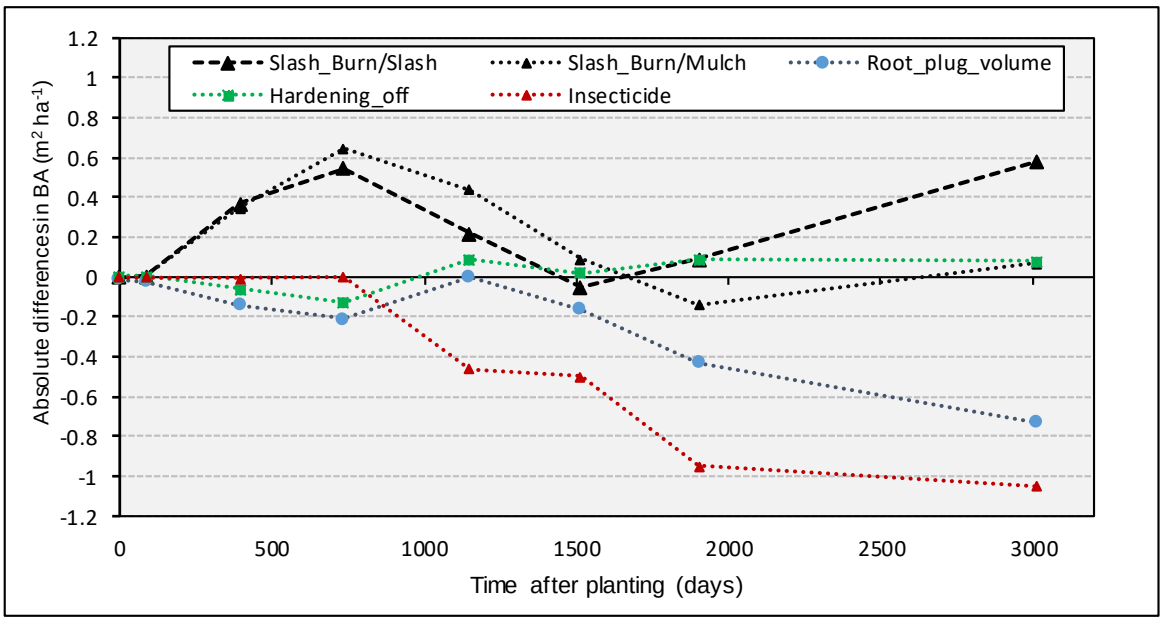

Figure 4.55: Trial D010: Absolute differences for BA (m^2 ha^{-1}) from 0 - 3011 DAP 1). Burn – spread diff. 2). Burn – mulch diff. 3). RPV (60 cm^3 – 105 cm^3) 4). Hardening of plant stock minus non-hardening 5). No insecticide minus insecticide application

4.14.2. HIGH PRODUCTIVITY SITE (TRIAL D010 – *E. DUNNII*): RELATIVE DIFFERENCES – BASAL AREA

Relative differences (absolute diff. / standard treatment) for mean BA between burning and slash, and burning and mulch, showed minor gains for 2 years in favour of burning, over retained residues (Figure 4.56); however, long-term relative differences were negligible by 3011 DAP. RPV showed early relative differences up to 1 year but this diminished to zero at full rotation. Hardening and insecticide applications showed early relative differences within the first three months but no real BA gains accrued over the standard treatment. In summary, relative differences between residue treatments showed little impact on mean BA, indicating that any early gains diminished with time.

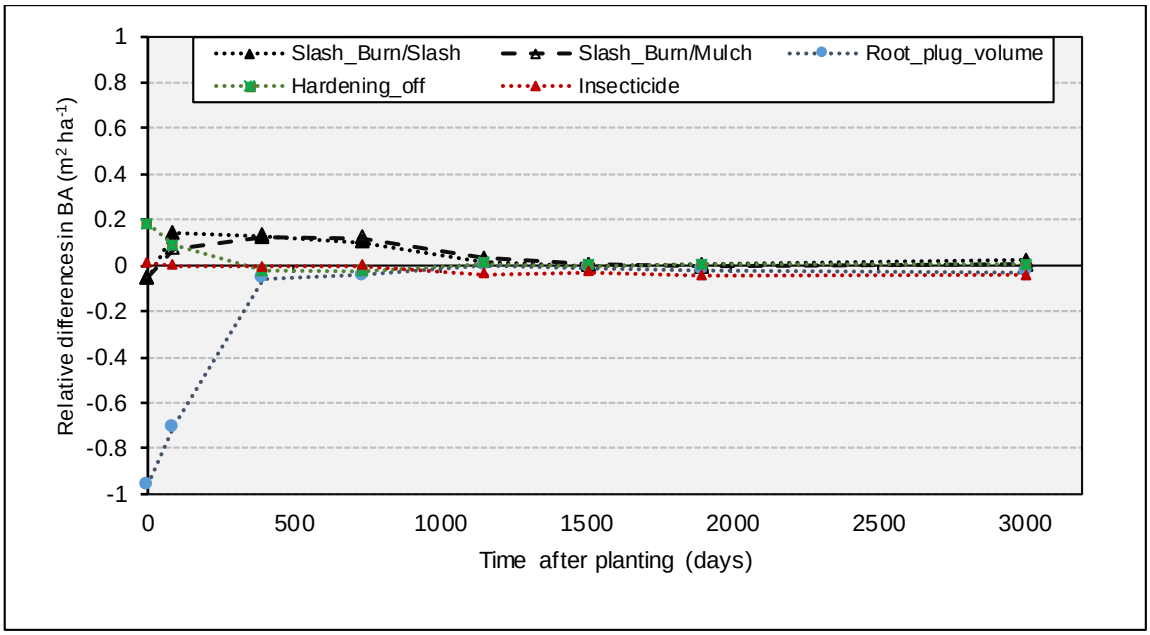

Figure 4.56: Trial D010: Relative differences for BA (m^2 ha^{-1}) from 0 - 3011 DAP. Burn – spread diff. 2). Burn – mulch diff. 3). RPV (60 cm^3 – 105 cm^3) 4). Hardening of plant stock minus non-hardening 5). No insecticide minus insecticide application

4.14.3. MEDIUM PRODUCTIVITY SITE (TRIAL E013 – *E.DUNNII*) - ABSOLUTE DIFFERENCES BASAL AREA

From 96 – 2985 DAP, burning showed the largest mean BA, a response attributed to freely available nutrients. Mulch and slash showed similar basal areas for both treatments. The large plug volume outperformed the standard plug volume from 0 - 2985 DAP, with treatments responses diverging over time, albeit not strongly so. In summary, residue treatments and RPV showed an initial divergence from 378 DAP but thereafter the distance between treatment lines stayed constant indicating that the initial treatment response had diminished and silviculture treatments were no longer having an impact on BA (Figure 4.57b).

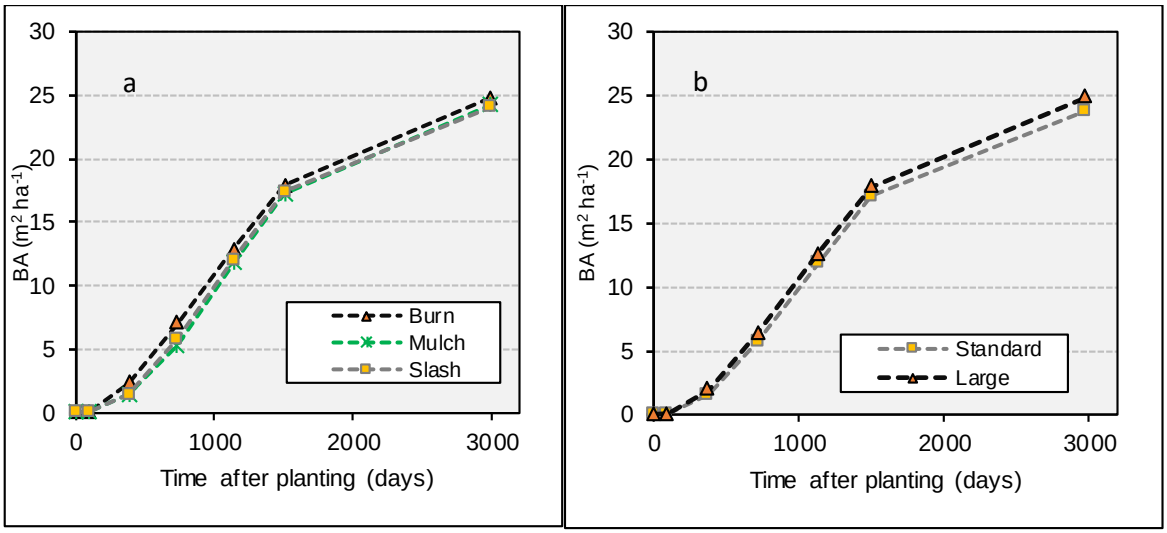

Figure 4.57: Trial E013: Residue management (a = left) and RPV (105 cm³ vs standard 60 cm³) (b = right) plots for BA (m² ha⁻¹) from 0 – 2985 DAP

From 90 – 2985 DAP, (Figure 4.58) showed that in the absence of nursery hardening, mean BA was consistently higher. Although a response, the difference in BA between not hardened and hardened remained relatively low. There was no initial benefit from the application of insecticide, but from 378 – 2985 DAP, BA increased faster in its presence. The high and medium productivity trial sites planted to *E. dunnii* expressed BA gains from insecticide treatments to full rotation (≈ 8 years). Mean BA showed that from 378 DAP (≈ 1 year) most treatments diverged, except for hardening, which showed little absolute differences between treatments.

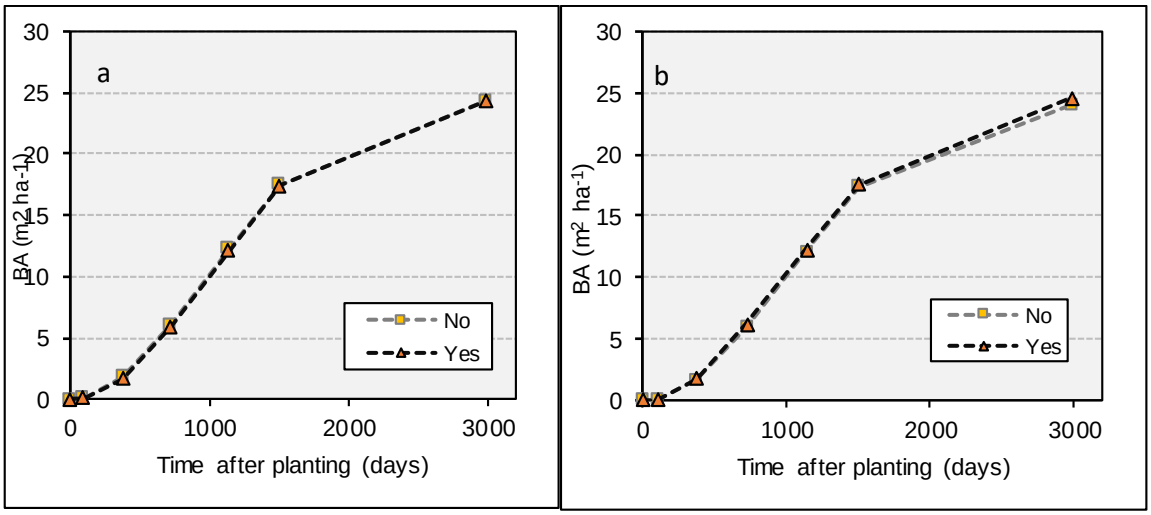

Figure 4.58: Trial E013: Application of nursery hardening (a = left) and insecticide (b = right) plots for basal area (m² ha⁻¹) from 0 – 2985 days DAP

Absolute differences between burn and spread (slash) grewrapidly in favour of burning with a higher mean BA difference (Figure 4.59) = 1.75 m² ha⁻¹ at 724 DAP. Thereafter, differences between burn and spread (slash) would decline, but to rebound to a gain for

burning of 0.57 m^2 ha^{-1} at final rotation, exactly the same absolute difference as for the high productivity site (*E. dunnii* - Trial D010). Absolute differences between burning and mulch expressed a similar graphical trend (Figure 4.59) in favour of burning = 1.26 m^2 ha^{-1} at 724 DAP (≈ 2 year), before declining to 0.75 m^2 ha^{-1} at 2985 DAP.

Absolute gains for plug volume (RPV) favoured the larger plug volume and this would increase to full rotation at 2985 DAP (note that a negative value for difference in root plug score in Fig 4.59 indicates superior growth of the large plug treatment over the standard size). There was a qualified expectation that relative differences would increase as trees grew and the magnitude would increase with time. By 2985 DAP, the large plug showed an absolute gain in BA = 0.75 m^2 ha^{-1} over the standard plug (Figure 4.59) whilst on the high productivity site (Trial D010) an absolute gain = 0.73 m^2 ha^{-1} was realised. The nursery hardening treatment showed minor benefits where no water regulation was applied to planting stock, but this declined to zero at full rotation. Furthermore, there were no differences where insecticide was applied, until 378 DAP (≈1 year). Thereafter the benefit of insecticide application grew 0.58 m^2 ha^{-1} by 2985 DAP (full rotation ≈ 8 years). This was 1.8 times lower than the high productivity (Trial D010) site at full rotation.

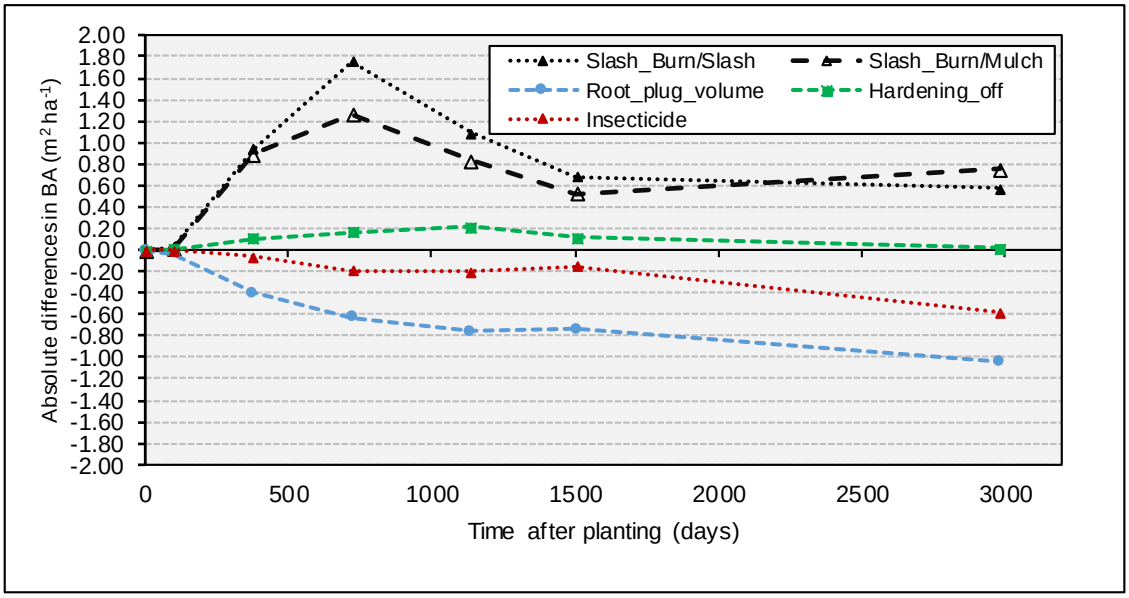

Figure 4.59: Trial E013: Absolute differences for BA (m^2 ha^{-1}) from 0 - 2985 DAP. 1). Burn – spread diff. 2). Burn – mulch diff. 3). Root plug volume (60 cm^3 – 105 cm^3) 4). Hardening of plant stock minus non-hardening 5). No insecticide – application of insecticide

4.14.4. MEDIUM PRODUCTIVITY SITE (TRIAL E013 – *E. DUNNII*) - RELATIVE DIFFERENCES BASAL AREA

Relative differences in mean BA between burning and slash, and burning and mulch, showed good gains up to 1 year (378 Dap), in favour of burning over residues (Figure 4.60), with treatment comparisons following the same graphical trends. However, long-term relative differences for residue treatments were negligible by 2985 Dap. The value of relative differences lies in the ability to encapsulate clearly absolute gains or losses at a specific time, relative to a standard treatment. Where treatment differences do not diverge, the relative differences will disappear with time and a decision to invest in a specific treatment(s) may be unwarranted.

Root plug volume showed strong relative gains for 3 years (1136 Dap) but diminished thereafter to zero at full rotation (Figure 4.60). The gains were consistent with the previous trial that showed a peak relative gain at 1 year. Hardening and insecticide applications showed early relative BA differences within the first three months but thereafter no real gains accrued over standard treatments. In summary, relative differences between treatments all showed early good gains but started to decline by 1136 Dap. Thereafter, treatments showed little relative differences for mean BA, indicating that early gains diminished with time and converged at zero by rotation end.

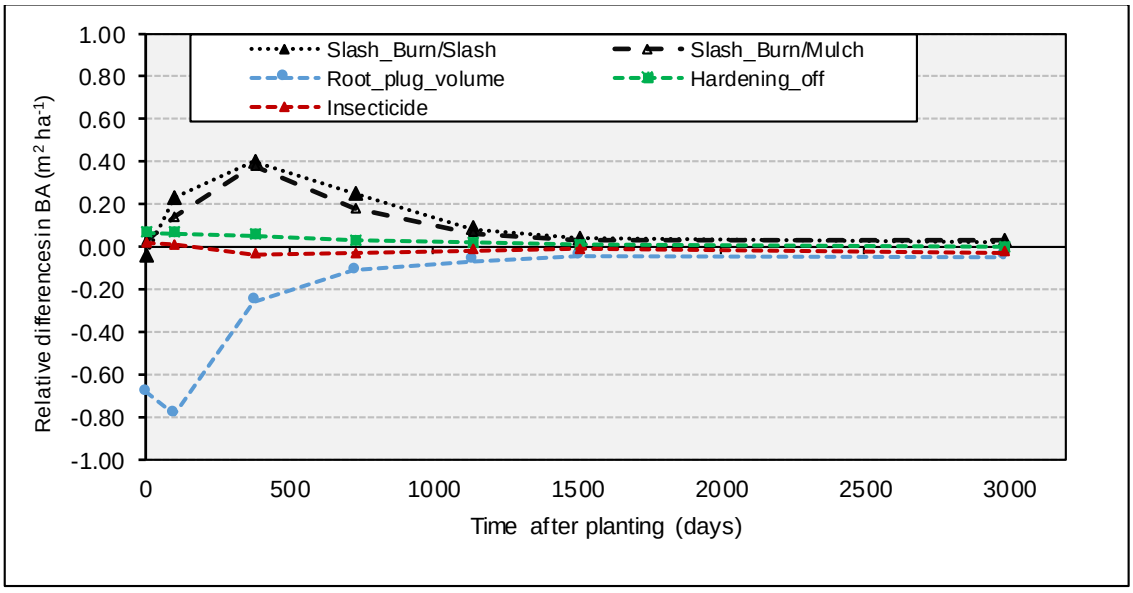

Figure 4.60: Trial E013: Relative differences for BA (m^2 ha^{-1}) from 0 - 2985 DAP. 1). Burn – spread diff. 2). Burn – mulch diff. 3). Root plug volume (60 cm^3 – 105 cm^3) 4). Hardening of plant stock minus non-hardening 5). No insecticide – application of insecticide

4.14.5. HIGH PRODUCTIVITY SITE (TRIAL D01B – *E.GXN*) - ABSOLUTE DIFFERENCE BASAL AREA (M^2 HA^{-1})

Mean BA for Trial D01b (high productivity trial site) (Figure 4.61) for residue treatments showed weak Type 1 growth responses. From 0 – 238 Dap (≈ 6 months), burning reflected the highest mean BA but differences between all three residues = 0.01 m^2 ha^{-1} were low. From 378 – 1504 DAP (4 years) mulching expressed the highest mean BA, whilst at full rotation (2656 DAP) spread residue was dominant. Clonal response to residue management differed to *E. dunnii* where the best mean BA was for burn treatments.

Plug volume (RPV) acted in a diametrically opposed fashion up to 585 DAP (≈18 months). From 0 – 378 DAP, the large plug recorded the highest BA. From 585 – 2656 DAP; the standard plug cavity outperformed the large plug cavity with a higher mean BA. Root plug volume responded differently with respect to genotype, with *E. dunnii* seedlings producing the highest BA from a large plug volume whereas for the clonal equivalent, the standard plug volume was superior (Figure 4.61).

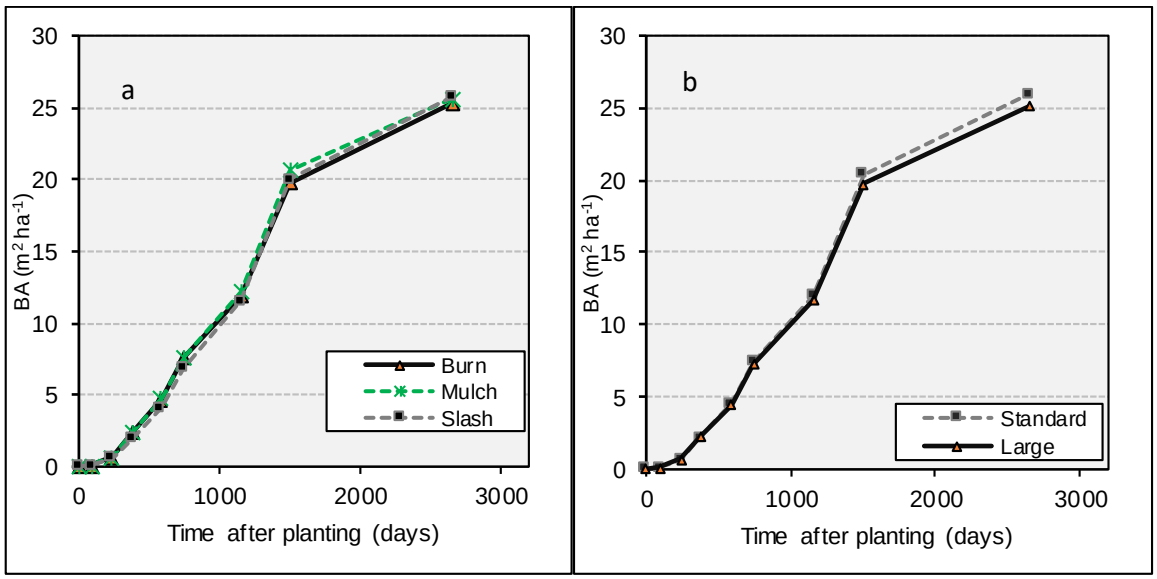

Figure 4.61: Trial D01b: Residue management (a = left) and RPV (105 cm^3 vs standard 60 cm^3) (b = right) plots for basal area (m^2 ha^{-1}) from 0 – 2656 DAP

The absence of nursery hardening (Figure 4.62a) produced a higher BA for the first three years. At 4 years, this status changed and nursery hardened *E. gxn* became more dominant. At full rotation (2656 DAP) the hardened treatment showed a mean BA = 26.2 m^2 ha^{-1}, 1.2 m^2 ha^{-1} higher than the unconditioned nursery equivalent. The impact of hardening was far more responsive on the *E. gxn* clone than the equivalent *E. dunnii* seedling trials.

Application of an insecticide drench (Figure 4.62) created a consistent and positive response in mean BA from 0 – 2656 DAP, albeit that the largest difference did not exceed 0.63 m^2 ha^{-1} by full rotation. As noted for the *E. dunnii* trials, an insecticide treatment ensured a slightly higher BA and as a silviculture treatment, insecticide applications benefited BA through to full rotation (7- 8 years).

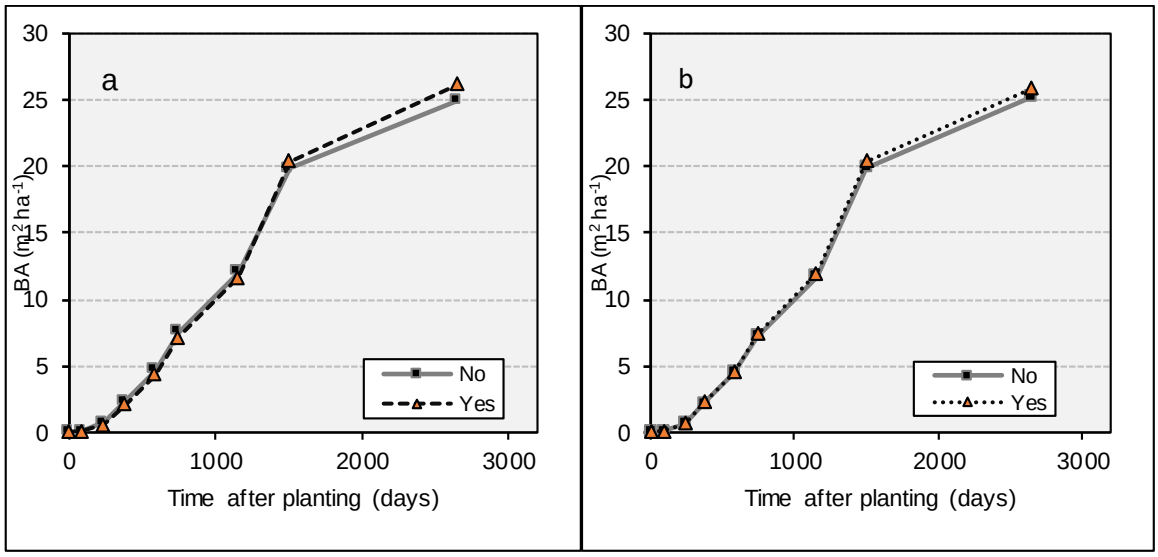

Figure 4.62: Trial D01b: Application of nursery hardening (a = left) and insecticide (b = right) plots for basal area (m^2 ha^{-1}) from 0 – 2656 DAP

Absolute BA differences were more responsive to burning over spread residues for the first 743 DAP and reached a difference = 0.71 m^2 ha^{-1} (Figure 4.63) at a very similar time to the *E. dunnii* trials. Thereafter, differences between burn and spread treatments declined to zero by 1300 DAP when treatment results reversed and spread of residues became more dominant with a 0.44 m^2 ha^{-1} gain. This was the converse to the *E. dunnii* trials, where BA was consistently higher for burning. Differences between burning and mulch were superior for mulching (Figure 4.63) reaching a maximum of 0.85 m^2 ha^{-1} at 1504 DAP (≈ 4 years), but declining to 0.32 m^2 ha^{-1} at 2656 DAP. This was again the converse of *E. dunnii* trial results, where burning produced a higher BA than mulching at full rotation (0.75 m^2 ha^{-1} at 2985 DAP). At 585 DAP, the large plug volume (105 cm^3) produced a higher mean BA but this would decline at 18 months. Thereafter, the standard plug showed greater basal area gains, with the absolute difference = 0.85 m^2 ha^{-1} by 2656 DAP. In the *E. dunnii* trials, the large plug showed an absolute gain in BA = 0.75 m^2 ha^{-1} at 3011 DAP. In summary, nursery plug volumes performed differently across genotypes with the higher mean BA for *E. dunnii* emanating from the large plug volume whereas the standard plug performed better in the *E. gxn* clonal trial.

Absolute differences for BA between nursery hardening treatments showed gains where no hardening was applied, reaching a peak = 0.41 m^2 ha^{-1} at 743 DAP (≈2 years), but declined rapidly to zero at 1300 DAP. Thereafter, the nursery hardening treatment grew stronger with a BA gain = 1.2 m^2 ha^{-1} by 2656 DAP. Insecticide treatment resulted in a BA gain = 0.63 m^2 ha^{-1} at 2656 DAP. A similar response was noted for *E. dunnii*, with a BA gain = 0.58 m^2 ha^{-1} by 2985 DAP (full rotation ≈ 8 years).

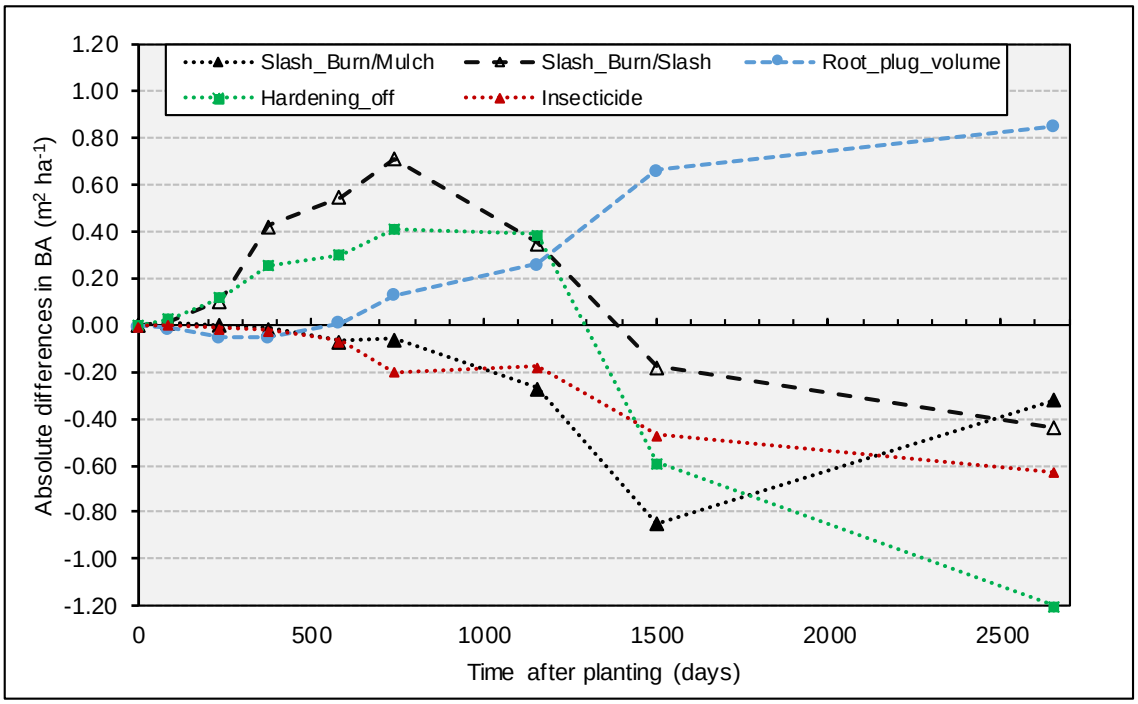

Figure 4.63: Trial D01b: Absolute differences for BA (m^2 ha^{-1}) from 0 - 2656 DAP 1). Burn – spread diff. 2). Burn – mulch diff. 3). Root plug volume (60 cm^3 - 105 cm^3) 4). Hardening of plant stock minus non-hardening 5). No insecticide application minus insecticide application

4.14.6. HIGH PRODUCTIVITY SITE (TRIAL D01B – *E.GXN*) - RELATIVE DIFFERENCES – BASAL AREA (M^2 HA^{-1})

Relative differences in mean BA between burning and spread residues, and burning and mulch showed no differences by 1156 DAP (Figure 4.64) and remained at zero through to 2656 DAP. These findings were similar to that of *E. dunnii* trials at 3000 DAP. Root plug volume showed minor early gains up to 585 DAP (≈ 18 months) for the standard plug but were zero by 2656 DAP. Results differed to the *E. dunnii* trials where there were strong early relative gains up to 1136 DAP, diminishing to zero thereafter by full rotation. Small relative gains accrued through no nursery hardening up to 1100 DAP but were negligible. Although insecticide treatment, as a soil drench, did reveal relative mean BA gains, results were low at 0.02 m^2 ha^{-1}.

In summary, relative differences between silviculture treatments showed small early gains but declined to zero by 1136 DAP; thereafter, silviculture treatments showed very small relative mean BA differences, converging around zero at full rotation (Figure 4.64). It is important to note that main effects converging to zero differences should not be regarded as non-significant events. Silviculture inputs are all critical at different periods during the rotation, but most importantly at planting and up to 12 months after establishment.

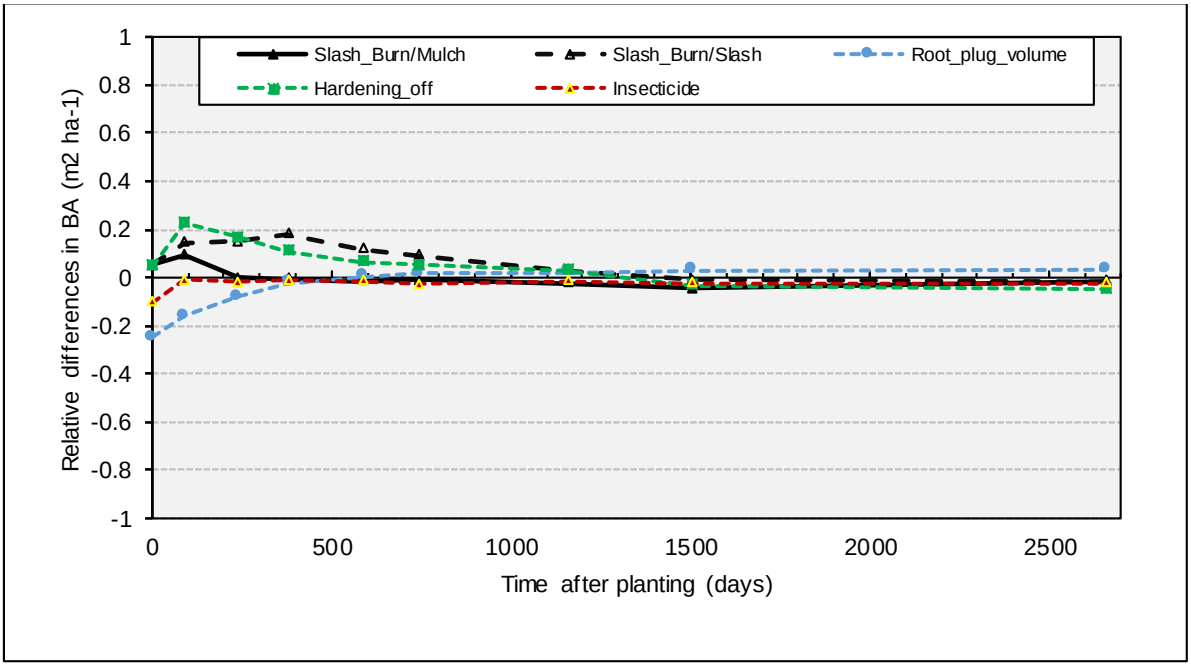

Figure 4.64: Trial D01b: Relative differences for BA (m^2 ha^{-1}) from 0 - 2656 DAP. 1). Burn – spread diff. 2). Burn – mulch diff. 3). Root plug volume (105 cm^3 – 60 cm^3) 4). Hardening of plant stock minus non-hardeing 5). Application of insecticide minus no application.

4.14.7. MEDIUM PRODUCTIVITY SITE (TRIAL F026 – *E.GXN*) - ABSOLUTE DIFFERENCES BASAL AREA

Mean basal area for residue treatments showed strongest differences between residue treatments of all four trials (Figure 4.65a). At 191 DAP; burning produced the highest BA response over the rotation. At full rotation, the highest mean BA for burning = 21.9 m^2 ha^{-1}, mulching = 21.8 m^2 ha^{-1} and spread residues = 19.5 m^2 ha^{-1}. In the high productivity (D01b) clonal trial the spread residue treatment performed the best, planted to the same *E. gxn* clone.

Root plug volume responded similarly to *E. dunnii* with the large plug volume (105 cm^3) recording the highest BA through to full rotation at 2585 DAP. The large plug produced 1.5 m^2 ha^{-1} more basal area than the standard plug. In terms of absolute BA differences, the

large plug volume recorded the highest mean BA in both *E. dunnii* seedling trials and one clonal *E. gxn* trial.

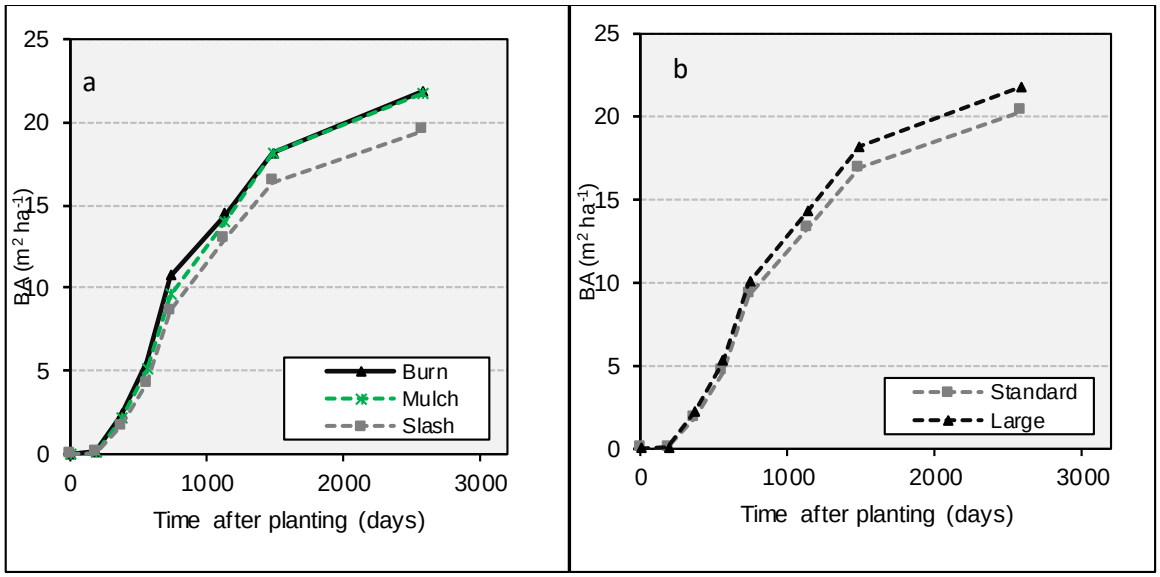

Figure 4.65: Trial F026: Residue management (a = left) and RPV (105 cm³ vs standard 60 cm³) (b = right) plots for basal area (cm² ha⁻¹) from 0 – 2585 DAP

Trial F026 (Figure 4.66a) revealed that by not hardening in the nursery, mean BA was higher for the entire trial rotation period. This did not correlate with the high productivity trial site (*E. gxn* - D01b) that produced the highest mean BA = 26.2 $m^2 ha^{-1}$ for the nursery hardened treatment. An insecticide drench (Figure 4.66b) produced no initial benefits in terms of BA gains for 6 months. There was a similar pattern across trials that raised a concern as to whether a pesticide drench triggers an initial phytotoxic response disrupting early root development that dissipates with time, whilst remaining beneficial in controlling soil borne pest. At final measurement the insecticide treatment was 1.0 $m^2 ha^{-1}$ higher than the untreated and responded consistently so over all trials.

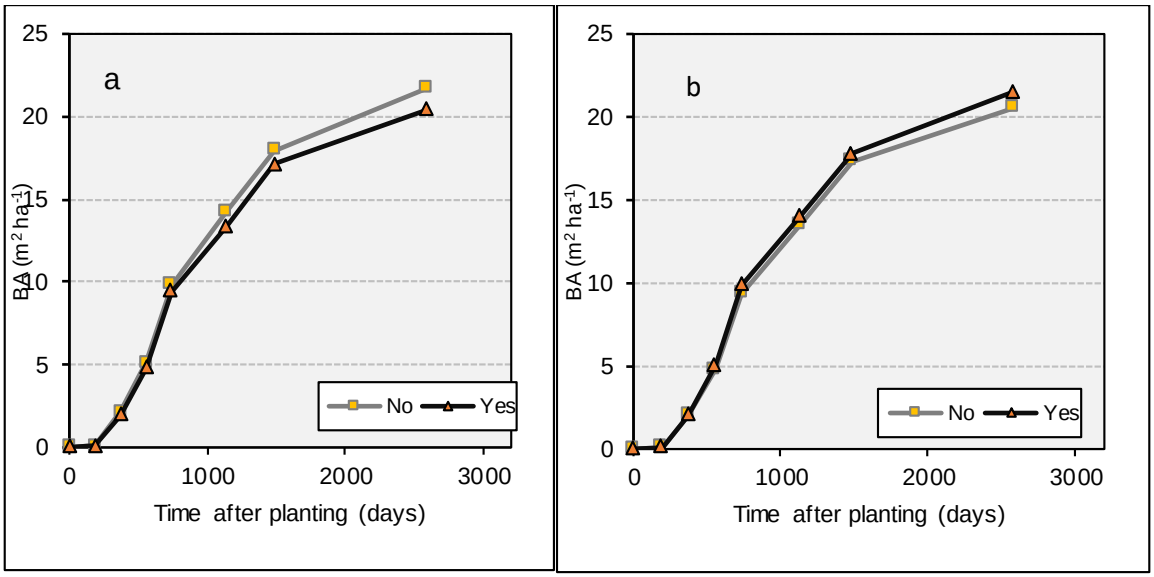

Figure 4.66: Trial F026: Application of nursery hardening (a = left) and insecticide (a.i. alpha cypermethrin) (b = right) plots for basal area (m^2 ha^{-1}) from 0 – 2585 days after planting (DAP)

Residue treatments revealed absolute differences for mean BA started to diverge 200 DAP (≈ 6 months) after planting. Burning showed greater BA gains over mulching for up to 1485 DAP (≈ 4 years) (Figure 4.67), reaching a maximum difference = 0.5 m^2 ha^{-1}, but declining rapidly by full rotation, with differences between burning and mulching decreasing to 0.13 m^2 ha^{-1}. This was the reverse of residue treatments results from *E. dunnii* trials where differences between burning and mulching favoured burning at full rotation (0.75 m^2 ha^{-1} BA gain at 2985 DAP). Burning residue produced a higher BA than spread residues (Figure 4.67) = 2.12 m^2 ha^{-1} at 738 DAP, at a very similar time to the *E. dunnii* trials. At full rotation, burning showed an increase of 2.4 m^2 ha^{-1} over spread residues.

The large plug volume from 191 DAP produced a higher mean BA than the standard plug and this would not decline as per the previous trial. At full rotation (2585 DAP) the large plug volume showed a gain = 1.5 m^2 ha^{-1} (Figure 4.67). On the high productivity site (Trial D01b – *E. gxn*) the standard plug produced a BA gain of 0.85 m^2 ha^{-1} by 2656 DAP. In summary, a large plug cavity performed best for both *E. dunnii* trials and a single *E. gxn* trial. Insecticide treatment displayed increasing absolute differences in mean BA with time, reaching a gain = 0.99 m^2 ha^{-1} by 2585 DAP. A similar response was described in *E. dunnii* trials with a BA gain of 0.58 m^2 ha^{-1} by 2985 DAP. The benefits of applying insecticide were definitive (Figure 4.67) and support an insecticide drench at planting with a second application 14 days later. Absolute differences between nursery hardening treatments showed increasing BA gains when no hardening was applied, reaching a maximum = 1.3 m^2 ha^{-1} at full rotation. On the high productivity site (*E. gxn*), the nursery hardening treatment

gained 1.2 m^2 ha^{-1} by 2656 DAP. The results for the clonal trials emphasized that single factor responses do not drive results but are only contributory and temporal. A final yield is the cumulative effect of multiple silviculture drivers combined with environmental conditions fluctuating across time.

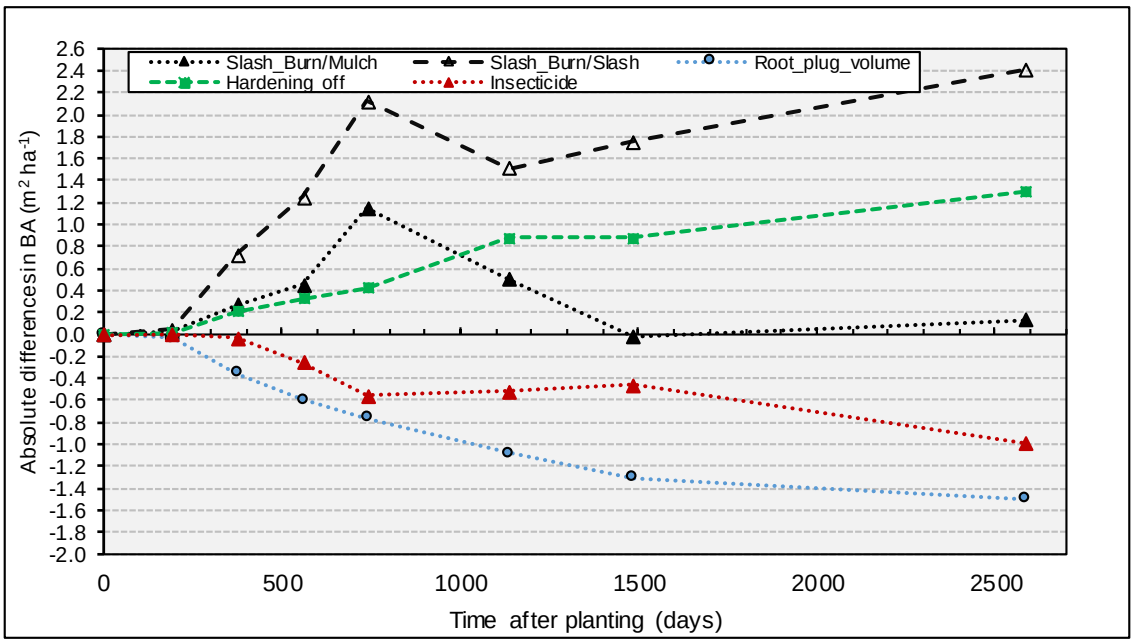

Figure 4.67: Trial F026: Absolute differences for BA (m^2 ha^{-1}) from 0 – 2585 DAP 1). Burn - spread diff. 2). Burn – mulch diff. 3). Root plug volume (60 cm^3 - 105 cm^3) 4). No nursery hardening - hardening 5). Application of no insecticide - insecticide application

4.14.8. MEDIUM PRODUCTIVITY SITE (TRIAL F026 – *E.GXN*) - RELATIVE DIFFERENCES BASAL AREA

The medium productivity site (Trial F026 – *E.gxn*) produced the lowest grand mean volume (148 m^3 ha^{-1} – Table 4.30) of all trials but was initially the most responsive for a number of silviculture treatments. Burning (max. gain = 0.461 m^2 ha^{-1}) outperformed spread residues at 191 DAP, but declined to a gain = 0.11 m^2 ha^{-1} at full rotation (Figure 4.68). Relative differences between burning and mulching were of lesser consequence with a maximum BA gain of 0.25 m^2 ha^{-1} that declined to zero by 2585 DAP. The trial revealed that mulching produced relatively minor BA gains over other standard residue treatments. The high cost of mulching would be unwarranted at the operational scale on such sites if the primary focus were increased stand volume. Root plug volume showed an initial early spike (0.46 m^2 ha^{-1} at 191 DAP) in favour of a large plug but declined to zero by full rotation. There were minor relative gains by not applying nursery hardening up to 374 DAP but these were negligible at full rotation. Although insecticide treatment did show relative mean BA gains, results were

only apparent from 374 DAP (≈1 year) and thereafter remained low, ranging from 0.02 to 0.06 m^2 ha^{-1}. In summary, relative differences between treatments all showed promising early gains from 100 DAP but declined to a static level at 1200 DAP and remained constant until full rotation (Figure 4.68).

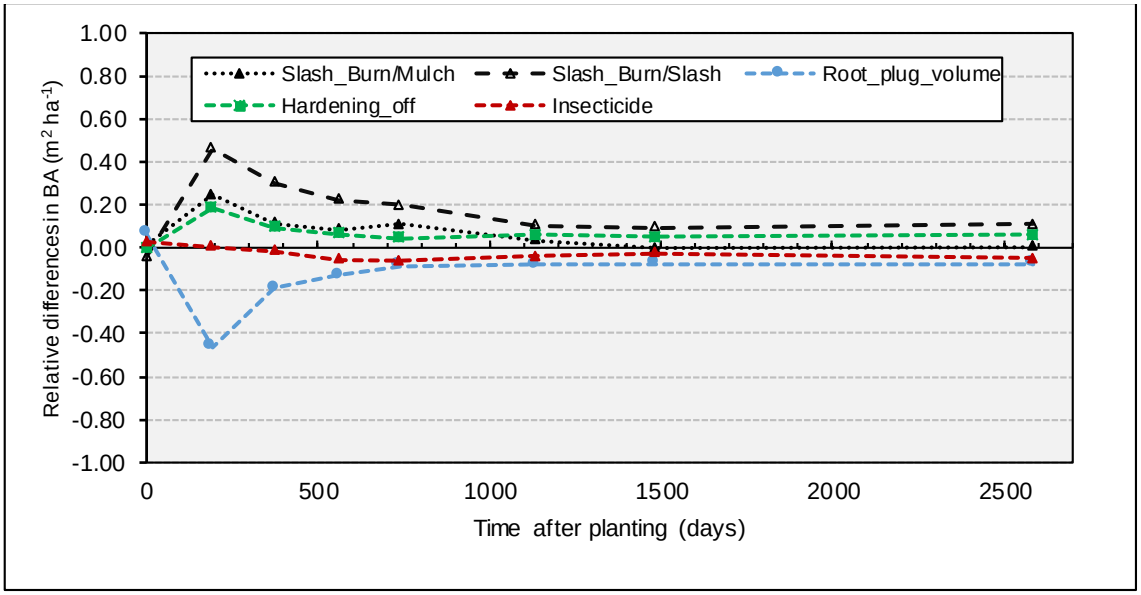

Figure 4.68: Trial F026: Relative differences for BA (m^2 ha^{-1}) from 0 - 2585 DAP 1). Burn – spread diff. 2). Burn – mulch diff. 3). Root plug volume (60 cm^3 - 105 cm^3) 4). Hardening of plant stock minus non-hardening 5). Application of insecticide minus no application

4.15. RESULTS - COMBINED TRIAL ANALYSIS

The statistical significance of silviculture treatments across all four sites, including two genotypes, were analysed through ANOVA tests. F-probability values, significant for basal area, MAI and stems per hectare at the 5% confidence level ($p < 0.05$), were further investigated by examination of mean squares (MS), either as a main effects or through their interactions. Differences were scrutinised for BA at full rotation for all sites to explain absolute or relative differences between treatments within factors. In summary, a three-step approach was applied to explain combined trial results, with respect to variance in BA (Figure 4.69).

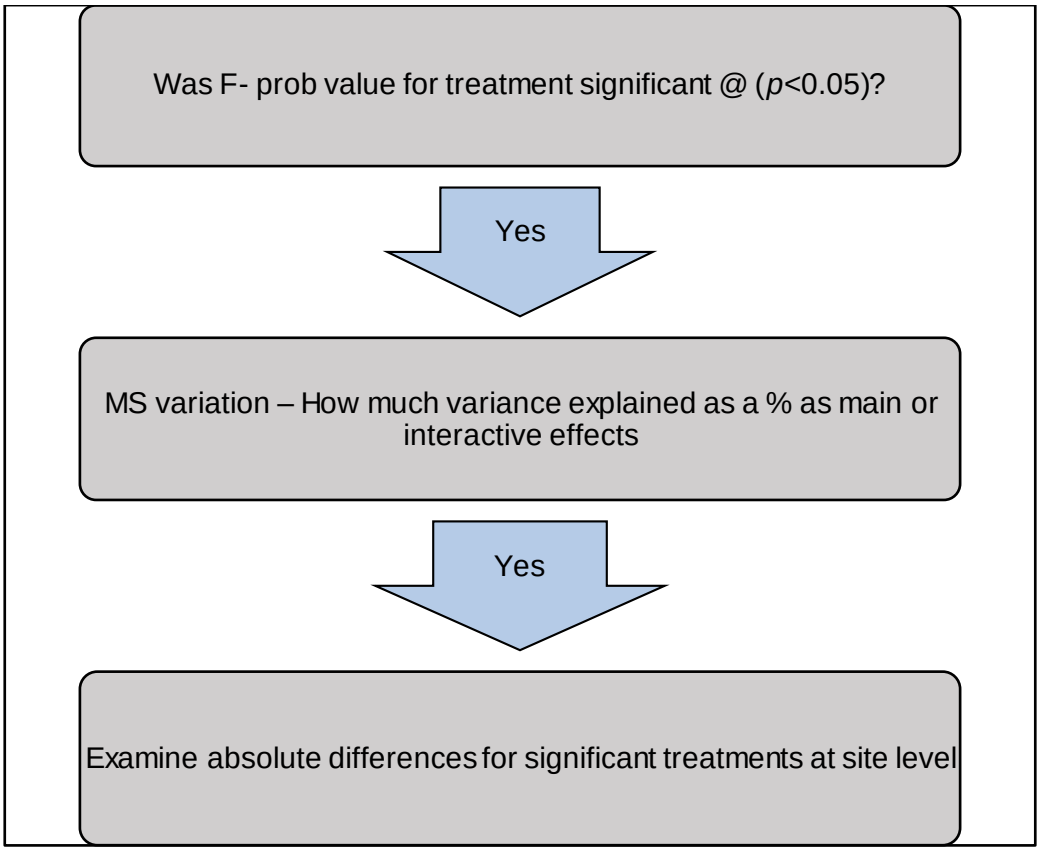

Figure 4.69: Statistical approach to explaining results for combined trial results

4.15.1. COMBINED TRIALS – ACCOUNTING FOR SIGNIFICANCE ACROSS TREATMENT COMBINATIONS AT FINAL ROTATION

F-probability values at the 5% confidence level for combined trials (Table 4.31) identified several complex interactions and hence it was deemed important to first identify silviculture factors that were strongly significant for stocking, Dbh and height, prior to further expounding on BA and MAI. For ease of reading, the term 'slash' was applied to describe residue management.

Table 4.31: Meta analysis ANOVA showing *F-prob* values for Dbh (cm), height (m), stocking (Spha) and MAI (m^3 ha^{-1}) at 99 months for combined trial data (significance at $p < 0.05$ grey shaded and bold font)

Source of variation	d.f.	Dbh_99 (cm)	Ht_99 (m)	Stocking_99 (Spha)	Final MAI (m^3 ha^{-1} yr^{-1})
		F pr.	F pr.	F pr.	F pr.
Site	3	0.416	**0.001**	**<0.001**	**0.022**
Slash_mgt	2	0.199	0.675	**0.009**	0.909
Site.Slash_mgt	6	0.918	0.908	0.427	0.912
RPV	1	0.648	0.342	0.142	0.278
Hardening	1	0.843	0.694	0.428	0.524
Insect	1	0.541	0.133	**0.042**	0.062
Site.RPV	3	0.322	0.152	**0.007**	0.580
Slash_mgt.RPV	2	0.468	0.839	0.437	**0.040**
Site.Hardening	3	0.812	0.727	0.157	0.091
Slash_mgt.Hardening	2	0.518	0.18	**0.031**	0.342
RPV.Hardening	1	**0.002**	0.081	0.497	**0.001**
Site.Insect	3	0.696	0.438	0.289	0.942
Slash_mgt.Insect	2	0.757	0.364	0.742	0.389
RPV.Insect	1	0.141	**0.040**	0.734	0.123
Hardening.Insect	1	0.922	0.817	0.309	0.719
Site.Slash_mgt.RPV	6	0.573	0.847	0.407	0.227
Site.Slash_mgt.Hardening	6	0.840	0.862	0.228	0.309
Site.RPV.Hardening	3	0.254	0.611	0.417	**0.017**
Slash_mgt.RPV.Hardening	2	0.347	**0.011**	0.222	0.137
Site.Slash_mgt.Insect	6	0.163	0.158	0.960	0.354
Site.RPV.Insect	3	0.162	0.312	0.364	0.327
Slash_mgt.RPV.Insect	2	0.327	0.628	0.071	0.452
Site.Hardening.Insect	3	0.376	0.248	0.935	0.296
Slash_mgt.Hardening.Insect	2	0.762	0.580	0.417	0.700
RPV.Hardening.Insect	1	0.417	0.744	**0.007**	0.938
Site.Slash_mgt.RPV.Hardening	6	0.759	0.821	0.958	0.744
Site.Slash_mgt.RPV.Insect	6	0.934	0.651	0.192	0.361
Site.Slash_mgt.Hardening.Insect	6	0.563	0.957	0.996	0.837
Site.RPV.Hardening.Insect	3	0.167	0.513	0.934	0.345
Slash_mgt.RPV.Hardening.Insect	2	0.680	0.457	0.104	0.195
Site.Slash_mgt.RPV.Hardening.Insect	6	0.896	0.981	0.950	0.771
Residual		19.96	9.40	4.940	12.22
Total		102.65	101.16	99.92	101.61
Grand mean		**14.19**	**20.21**	**1464**	**23.61**
Standard error of differences of means (units)		**0.74**	**0.811**	**102.27**	**4.077**
Coefficient of variation (units) (%)		**7.4**	**5.7**	**11.4**	**24.2**

NB: Slash_mgt = residue management; RPV = root plug volume; Hardening = nursery hardening; Insect = insecticide treatment

4.15.1.1. STOCKING

Stocking is a critical variable that only decreases with increasing rotation age. It remains a major challenge to achieve stocking levels close to 100% in the critical six weeks after establishment, especially considering that this is a major driver of final yield. The following treatments were significant for stocking at the 5% confidence level (Table 4.31):

1. Insect treatment ($p = 0.042$).
2. Site x RPV ($p = 0.007$).

3. Residue management x nursery hardening (p = 0.031) (Figure 4.70).
4. RPV x nursery hardening x insect (p = 0.007) (Figure 4.71).

Residue management x hardening (p = 0.031) (Table 4.31; Figure 4.70) recorded the highest stocking for treatments where residue burning was combined with growing stock not hardened in the nursery (Spha = 1548); however, this interaction could only account for 2.5% of mean differences in stocking (Appendix 2). The lowest stocking (Spha = 1374) was recorded where residue was retained and no nursery hardening applied, a decrease of 13% in stems per hectare. Planting in residue requires nursery stock to be conditioned such that there are no extended periods between irrigation applications.

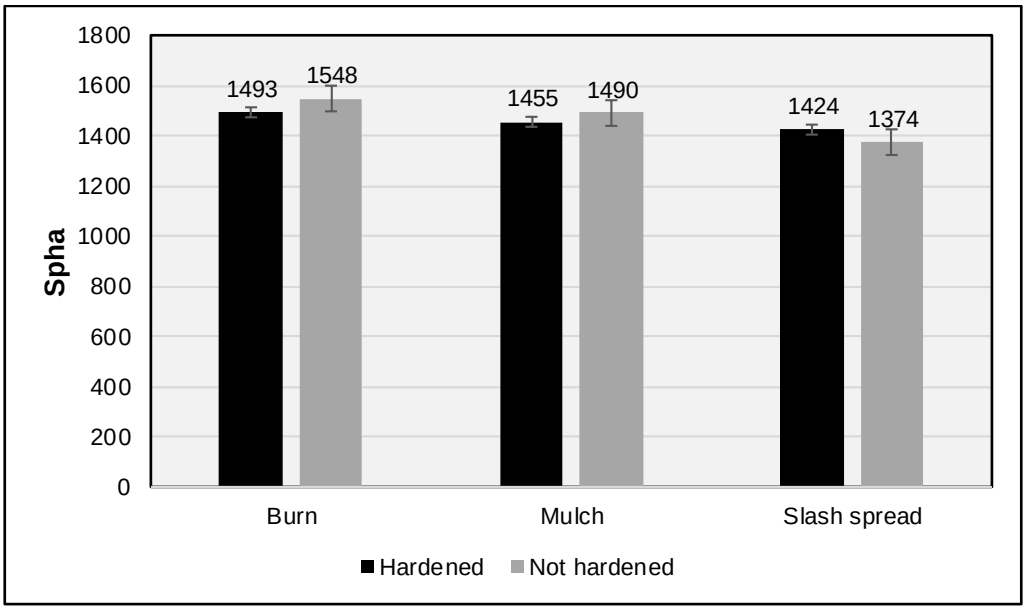

Figure 4.70: Stocking at final rotation: Residue management x hardening interaction (p = 0.031, d.f. = 42, lsd = 84.3). Error bars = s.e

At a more expanded level, the three way interaction (RPV x nursery hardening x insect) was highly significant (p = 0.007). The absence of site (generally comparable in terms of soil fertility and water deficits) revealed the importance of the combined impact of the silviculture factors, plug volume, insecticide application and nursery hardening on initial stocking that would manifest as a serious impact on final MAI at 99 months (Figure 4.71).

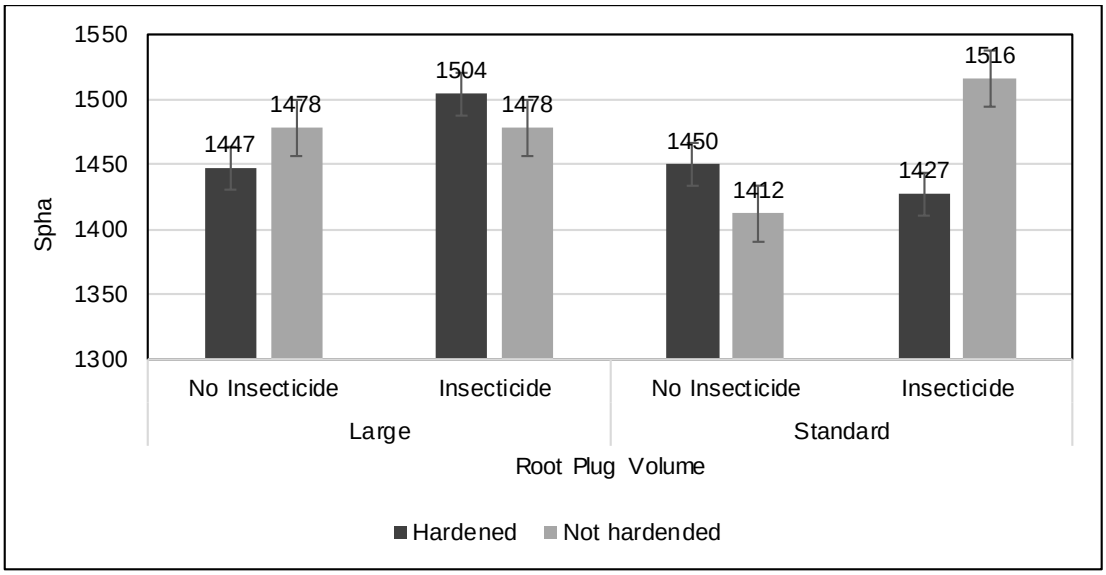

Figure 4.71: RPV X hardening x insect interaction (*p* = 0.007, d.f. = 281, lsd = 66.71) effects on stocking at 99 months. Error bars = s.e

The highest stocking (1516 Spha) was recorded for a treatment combination of standard (60 cm^3) plug, not exposed to nursery hardening in the nursery and planted with an insecticide application (Figure 4.71). The second best stocked treatment (1504 Spha) was the large (105 cm^3) plug, hardened in the nursery, and treated with an insecticide at planting. Poorest stocking (1412 Spha) was noted where a standard nursery plug was not hardened in the nursery and no insecticide applied at planting.

The strongly significant three-way interaction indicated that plug volume and nursery hardening produced variable responses in terms of stocking but the application of insecticide was much more critical and uniform. Tree survival tended to favour nursery stock raised in a larger cavity plug that had not undergone nursery hardening. Insecticide application at planting resulted in a mean stocking of 1482 Spha across all sites, whereas no insecticide applications produced a mean stocking = 1447 Spha.

4.15.1.2. DBH AND HEIGHT RESPONSES

Only one interaction, RPV X hardening, was strongly significant for Dbh (*p* = 0.002) at 99 months across all four sites with no conflict for interactions of significance for stocking noted (Figure 4.72). The best performing Dbh at 99 months was recorded for a large plug volume that was not hardened at 14.4 cm whereas the lowest Dbh = 14.0 cm for a standard plug that was not hardened in the nursery; however, dimensional differences were small.

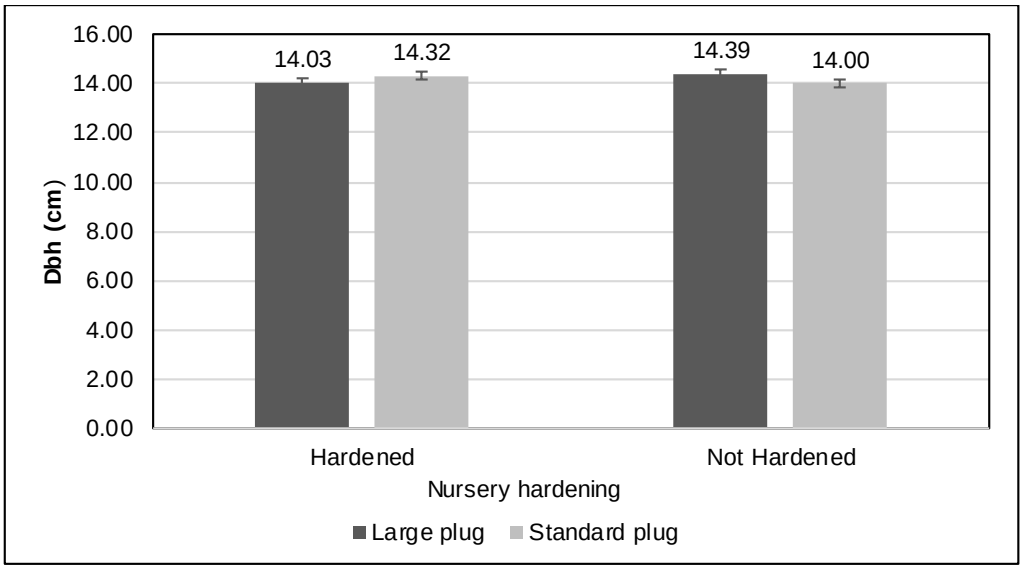

Figure 4.72: RPV x hardening effects on Dbh at 99 months (*p* = 0.002, d.f. = 281, lsd = 66.71). Error bars = s.e

Height measurements at 99 months across all sites was significant for residue management x RPV x hardening (*p* = 0.011) as reported for MAI (Figure 4.73). Height differences were low with the tallest height recorded for a large nursery plug, not hardened in the nursery, and planted to a burn treatment (20.6 m). The lowest reported height of 19.8 m was a standard plug, not hardened, and planted to a mulch treatment (Figure 4.73).

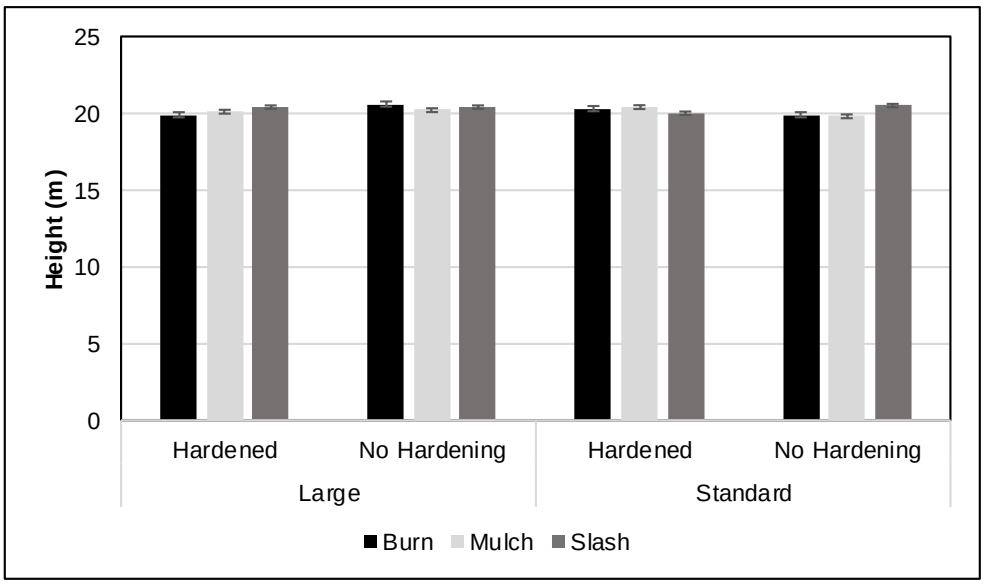

Figure 4.73: Residue management x RPV x hardening effects on height at 99 months (*p* = 0.011, d.f. = 82.53, lsd = 0.694 ,s.e = 0.3489). Error bars = s.e

4.15.1.3. BASAL AREA AND MEAN ANNUAL INCREMENT (MAI)

Basal area (BA) as an important tree characteristic in defining the amount of area occupied by tree stems was reported in detail (Table 4.31) for the combined trials. A number of citations highlight BA as a good predictor of forest dynamics and a very reliable tool for growth and yield modelling (Murphy and Shelton 1996; Chen *et a*l., 2007). It is simpler to measure than height, with a better degree accuracy, but genotypes with different tapers must be considered when comparing results. For BA, the three way interaction between Site x RPV x hardening, as well as residue management x RPV x hardening were discussed as the former was significant at planting and at 48 months, and both interactions were significant at 48 months, remaining weakly significant ($p = 0.1$) significant at rotation end.

One main effect was significant for MAI, 1) Site ($p = 0.022$), whilst 1) residue management x RPV ($p = 0.040$) (Figure 4.75), 2) RPV x hardening ($p = 0.001$) and 3) Site x RPV x hardening ($p = 0.017$) (Figure 4.76) were significant at the 5% confidence level and further addressed. Although the two-way interaction for residue management x RPV ($p = 0.040$) (Figure 4.75) was significant at rotation end, mean square (ms) values could only account for 3% of differences at full rotation. The best performing treatments across sites were attributed to a large plug volume ($p = 0.042$) planted on a residue spread treatment (MAI = 24.8 m^3 ha^{-1} yr^{-1}) with the poorest performance for the standard plug (RPV = 60 cm^3) planted to a burn treatment (MAI = 22.6 m^3 ha^{-1} yr^{-1}).

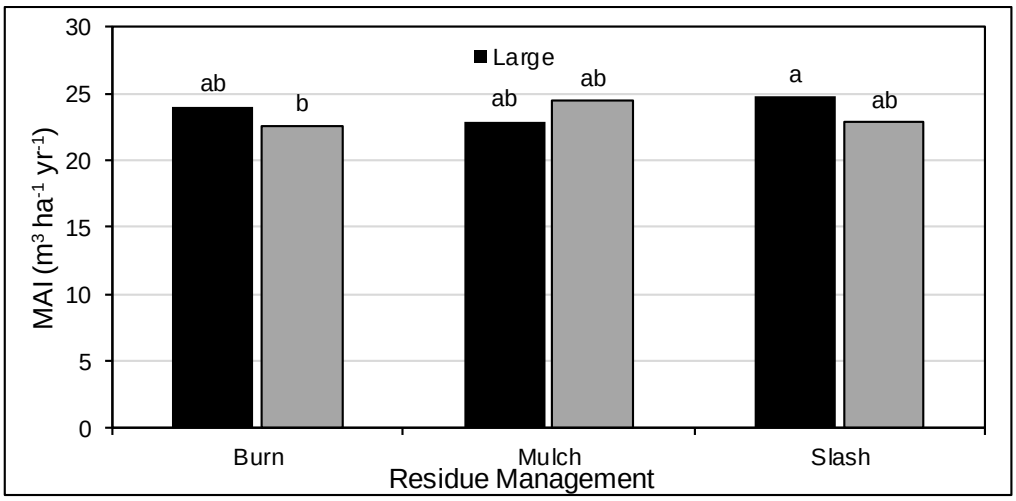

Figure 4.75: Impact of residue management x RPV interaction on MAI ($p = 0.001$, lsd = 2.653). Means with the same letters are not significantly different

For *E. dunnii,* the best recorded MAI = 23.6 m^3 ha^{-1} yr^{-1} for a standard plug, hardened in the nursery and planted at Site D010 (high productivity site). This was 3.2 m^3 ha^{-1} yr^{-1} better than the worst performer (20.4 m^3 ha^{-1}) for *E. dunnii* (Site E013 – medium productivity),

comprising a standard plug (60 cm^3), and not nursery hardened. For *E. gxn*, the best MAI = 33.4 m^3 ha^{-1} yr^{-1} planted at Site D01b (high productivity site) for a treatment combination of a large plug (105 cm^3), not hardened in the nursery. In contrast, the same treatment combination produced the worst MAI = 19.9 m^3 ha^{-1} yr^{-1} at the medium productivity site, F026 (Figure 4.76).

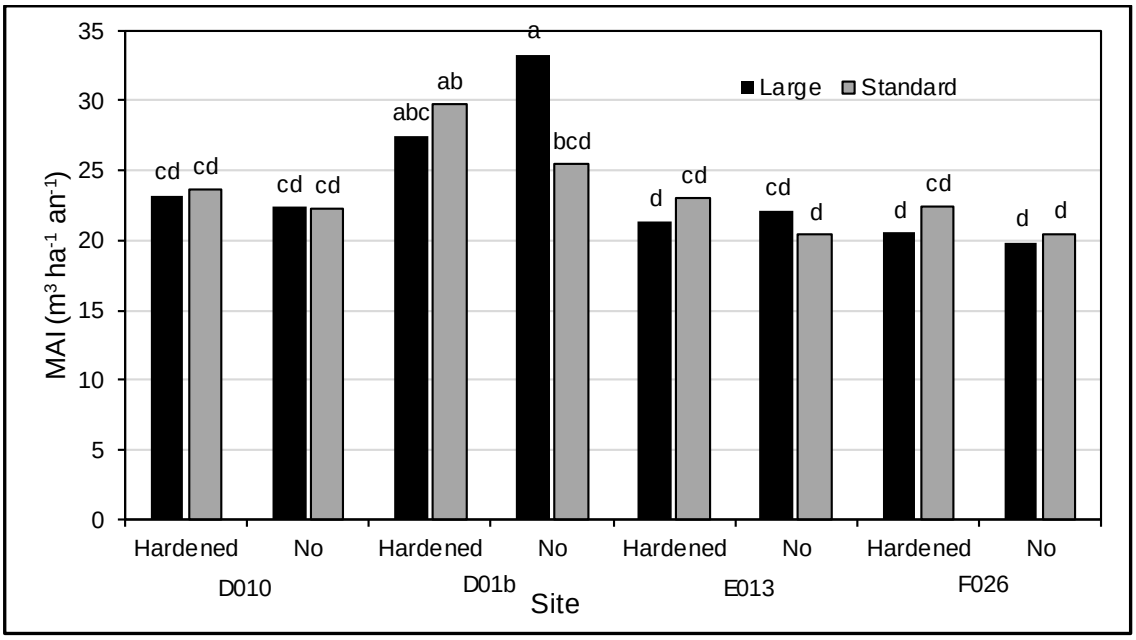

Figure 4.76: Site x RPV x hardening interaction (p = 0.017, lsd = 5.858). Means with the same letters are not significantly different

The 3-way interaction of factors only registered significance due to the results of Site D01b and thus the importance of the 2-way interaction of RPV X hardening was also very highly significant ($p < 0.001$) in its own right, i.e. effectively the same response but without the site factor included. The most important finding from the 2-way interaction was that the standard root plug volume of 60 cm^3 generally benefitted from hardening but large root plug volumes of 105 cm^3 did not. The description of the 3-way and 2-way interactions that contained the same silviculture treatments meant no further single factors were described, even if significant as single factors did not respond the same way in the presence or absence of other significantly interacting variables.

4.15.2. COMBINED TRIALS – ACCOUNTING FOR BASAL AREA VARIANCE

The *F*-probability values for combined data sets at 5% level are described (Table 4.32) whilst mean square (ms) values to explain percentage variance for main and interactions of factors influencing (Days 0 - 3011) BA are represented graphically (Figure 4.79, Figure

4.80). Focus was placed on BA at 12 months as reflecting the transition to canopy closure, mid rotation at 48 months when MAI ranking tends to stabilise and full rotation at 99 months.

F-prob values revealed few significant treatments ($p < 0.05$) that could explain basal area variance (Table 4.32 and Appendix 3). Up to canopy closure (BA 12), site, residue management, RPV and nursery hardening were all highly significant at the 1% level. Residue management accounted for 31% of mean BA differences whilst RPV accounted for 14% and nursery hardening only 4%. At 24 months, site accounted for 74% of BA differences whilst residue management decreased to 9%. At 24 months (BA 24), nursery hardening was no longer significant ($p = 0.091$), whereas site and residue management were strongly significant ($p < 0.001$).

At 36 months, only RPV ($p = 0.035$) and nursery hardening ($p = 0.0360$) were significant whilst site x RPV interaction was also significant ($p = 0.039$). At mid rotation (BA 48), site could explain 30% of BA differences whilst silviculture main effects ceased to explain mean BA variance, with plug volume at only 6%. Only the interactions, site X RPV x hardening ($p = 0.021$) and residue management x RPV x Hardening ($p = 0.015$) were strongly significant (Table 4.32; Appendix 3).

Table 4.32: Summary of ANOVA showing *F-prob* values for Basal Area (m^2 ha^{-1}) from establishment to full rotation at 99 months for combined trial data (significance at $p < 0.05$ grey shaded and bold font)

Source of variation	Variate: BA_0	Variate: BA 12	Variate: BA 24	Variate: BA 36	Variate: BA 48	Variate: BA 99
	F pr.	F pr.	F pr.	F pr.	F pr.	F pr.
Site stratum	**<.001**	0.003	**<.001**	0.103	0.096	**0.018**
Slash_mgt	0.961	**<.001**	**<.001**	0.123	0.464	0.629
Site.Slash_mgt	0.659	0.036	0.178	0.758	0.767	0.791
RPV	**<.001**	**<.001**	**0.005**	**0.035**	0.164	0.121
Hardening	**<.001**	0.01	0.091	**0.036**	0.709	0.896
Insect	0.432	0.52	0.069	0.072	0.152	**0.036**
Site.RPV	<.001	0.037	0.063	**0.039**	0.077	0.159
Slash_mgt.RPV	0.382	0.395	0.620	0.393	0.132	0.055
Site.Hardening	**0.012**	0.11	0.394	0.470	0.310	0.158
Slash_mgt.Hardening	0.489	0.927	0.582	0.537	0.642	0.209
RPV.Hardening	0.848	0.996	0.875	0.422	0.099	**0.007**
Site.Insect	0.096	0.983	0.483	0.886	0.966	0.962
Slash_mgt.Insect	0.722	0.837	0.498	0.600	0.404	0.563
RPV.Insect	0.521	0.071	0.333	0.252	0.305	0.137
Hardening.Insect	0.757	0.77	0.469	0.556	0.818	0.523
Site.Slash_mgt.RPV	0.740	0.132	0.537	0.552	0.646	0.527
Site.Slash_mgt.Hardening	0.894	0.568	0.230	0.094	0.307	0.143
Site.RPV.Hardening	**0.007**	0.694	0.482	0.664	**0.021**	0.100
Slash_mgt.RPV.Hardening	0.779	0.84	0.198	0.075	**0.015**	0.075
Site.Slash_mgt.Insect	0.941	0.729	0.755	0.596	0.534	0.598
Site.RPV.Insect	0.805	0.909	0.811	0.594	0.477	0.441
Slash_mgt.RPV.Insect	0.694	0.821	0.218	0.311	0.185	0.245
Site.Hardening.Insect	0.261	0.389	0.517	0.929	0.359	0.525
Slash_mgt.Hardening.Insect	0.946	0.935	0.460	0.194	0.148	0.674
RPV.Hardening.Insect	0.831	0.472	0.059	0.153	0.152	0.211
Total						

NB: Slash_mgt = residue management; RPV = root plug volume; Hardening = nursery hardening; Insect = insecticide treatment

At full rotation, BA differences were only explainable in terms of the main effect site (p = 0.018), explaining 40% of differences, whilst individual main silviculture effects were not able to explain more than 6% of basal area variance. RPV x hardening (p =0.007) was significant for BA at full rotation, whilst the interaction of RPV x hardening only accounted for 9% of BA differences (Appendix 3). In summary, basal area differences were mostly explainable by site variability, and to a lesser measure, nursery practices, but silviculture treatments such as insecticide applications and residue management were not significantly different by rotation end.

4.15.3. THE IMPACTS OF WATER DEFICIT ON BASAL AREA

Water deficits over the full rotation for the four experiments (separated by genotype) are plotted as two separate figures (Figure 4.77A, Figure 4.77B), with current basal area illustrated separately (Figure 4.78 A & B) for genotype. An additional graph (Figure 4.79) is included to show the response of genotypic cumulative BA to water deficits and to support the conceptual diagram (Figure 5.1). It is important to note that *E. dunnii* trials were planted at the beginning of 2011, whilst *E. gxn* trials were planted at the beginning of March 2012.

Water deficits during 2011 (one year after planting) were low (15 - 18 mm y^{-1}) across the two *E. dunnii* experiments with BA prior to canopy closure below 0.020 m^2 ha^{-1}. In the *E. gxn experiments,* WD levels in the first year (plant year 2012) were much higher (83 - 97 mm y^{-1}) with BA measures at 0.011 m^2 ha^{-1} for trial F026 and 0.024 M^2 ha^{-1} for trial D01b. The higher water deficit in the first year of planting on *E. gxn* sites did not have a major impact on BA performance (Figure 4.77A, Figure 4.77B).

At the end of the first year, water deficits had increased by nearly 10 fold for *E. dunnii* sites, and trial D010 revealed a higher water deficit than trial E013 (131 mm vs 121 mm), yet still recorded a higher BA (D010 = 2.6 m^2 ha^{-1} vs. E013 = 1.7 m^2 ha^{-1}). It was assumed that slight variations in site fertility differences were responsible for BA difference. At 2 years of age, WD for *E. dunnii* sites varied slightly (71 - 79 mm) with trial E013 reversing earlier BA losses and recording a 1 m^2 ha^{-1} higher BA than trial D010 (5.0 vs. 6.0 m^2 ha^{-1}). Although *E. dunnii sites* experienced very similar water deficits in the first two years, and were comparable in terms of cumulative BA, trial E013 produced nearly 74% extra BA in the second year after planting. This was not explainable in terms of any other factor other than site fertility as WD levels were comparable.

Water deficit differences for *E. gxn* experiments at 2 years were much higher (111 - 128 mm y^{-1}) yet produced basal areas of D01b = 7.3 m^2 ha^{-1} and F026 = 9.6 m^2 ha^{-1}. In the second year trial F026 produced a current BA = 7.6 m^2 ha^{-1}, whilst trial D01b was 48% lower at 5.1 m^2 ha^{-1}, yet had also experienced the slightly lower WD = 111 mm yr^{-1}. It was again likely that site fertility was the reason for differences as WD did not vary greatly.

At 4 years (mid-rotation), WD for *E. dunnii* experiments ranged from 157 - 168 mm y^{-1} with cumulative BA in a narrow band of 12.2 – 13.0 m^2 ha^{-1}. Trial E013 produced a current BA = 6.1 m^2 ha^{-1} yr^{-1} whereas Trial D010 = 7.9 m^2 ha^{-1}. At 48 months, current BA for *E. gxn* experiments had decreased to a mean = 4.4 m^2 ha^{-1} yr^{-1} at a WD range = 158 - 177 mm y^{-1}

with cumulative BA = 12.0 - 14.0 m^2 ha^{-1}. Although both genotypes by mid rotation (4 years) performed evenly in terms of cumulative BA, *E. gxn* trials sites produced lower current BA, nearly 20% less under the same WD conditions (Figure 4.78A, Figure 4.78B). This could only point to the onset of the impacts of intraspecific competition with current BA more negatively affected under higher water deficit conditions. It can be only assumed that under more stressed soil water conditions, the *E. gxn* trials would have shown lower BA results.

At 5 years into rotation, *E. dunnii* sites underwent a major water deficit spike of 208 – 218 mm y^{-1} (drier sites) with current BA for the two trials = 5.2 m^2 ha^{-1} yr^{-1} and cumulative basal areas = 18.0 m^2 ha^{-1} (Figure 4.78). *E. gxn* experiments at 5 years (1825 DAP) experienced a much lower WD range = 84 - 90 mm y^{-1} with BA at 17.4 – 20.0 m^2 ha^{-1}. However, trials showed starkly different current BA responses, with trial F026 = 3.7 m^2 ha^{-1} and trial E013 = 8.3 m^2 ha^{-1}. The impact of lowered stocking for trial F026 did play a role but the fifth year was particularly poor in terms of current BA. However, under more benign conditions with higher soil moisture (lower WD); the *E. gxn* experiments were only able to produce cumulative basal areas comparable to the *E. dunnii* experiments (Figure 4.79).

By 6 years (Figure 4.77A), the WD for *E. dunnii* experiments was 112 mm y^{-1} with cumulative basal areas = 21 m^2 ha^{-1}; however, current basal areas decreased from 2.0 - 3.4 m^2 ha^{-1} yr^{-1}. At the same age, the *E. gxn* sites experienced lower water deficits ranging from 79 – 93 mm y^{-1} with cumulative BA = 19.0 – 23.0 m^2 ha^{-1}, and a decrease in current BA, ranging from 1.7 – 2.7 m^2 ha^{-1} yr^{-1}. All sites under fairly low WD conditions revealed decreasing current BA conditions and the impact of increasing relative density was likely to be of greater importance as final rotation ages grew closer. At 7 years (Figure 4.77A), *E. dunnii* experiments experienced a higher WD range of 120 – 131 mm y^{-1}. Although cumulative basal areas = 23.0 m^2 ha^{-1}, current basal areas remained low at a mean = 1.8 m^2 ha^{-1} yr^{-1} across both trials (Figure 4.78A, Figure 4.78B). *E. gxn* experiments at 7 years experienced low water deficits ranging from 26 – 33 mm y^{-1} but could only produce equivalent cumulative basal areas of 21.0 – 26.0 m^2 ha^{-1}, with current BA commensurately low, ranging from 1.8 – 2.7 m^2 ha^{-1} yr^{-1} (Figure 4.78). For both trial sites, current basal areas peaked between 4 to 5 years.

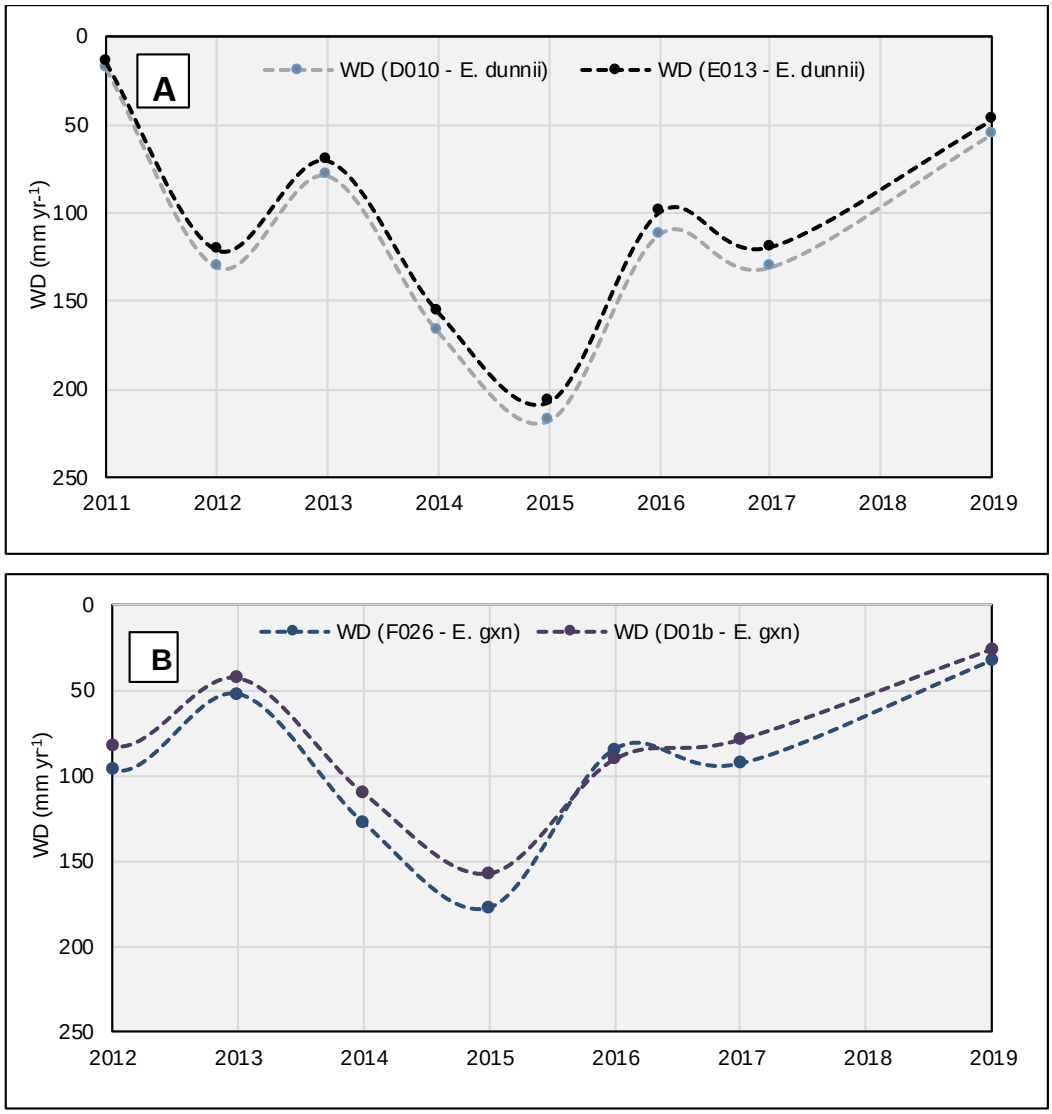

Figure 4.77 A & B: Water deficits over 4 experiments. *E. dunnii* (Figure 4.77A) trials were established in early 2011 and *E. gxn* trials (Figure 4.77B) early 2012. *E. dunnii* sites subject to more severe water deficits in 2015 in comparison to *E. gxn*

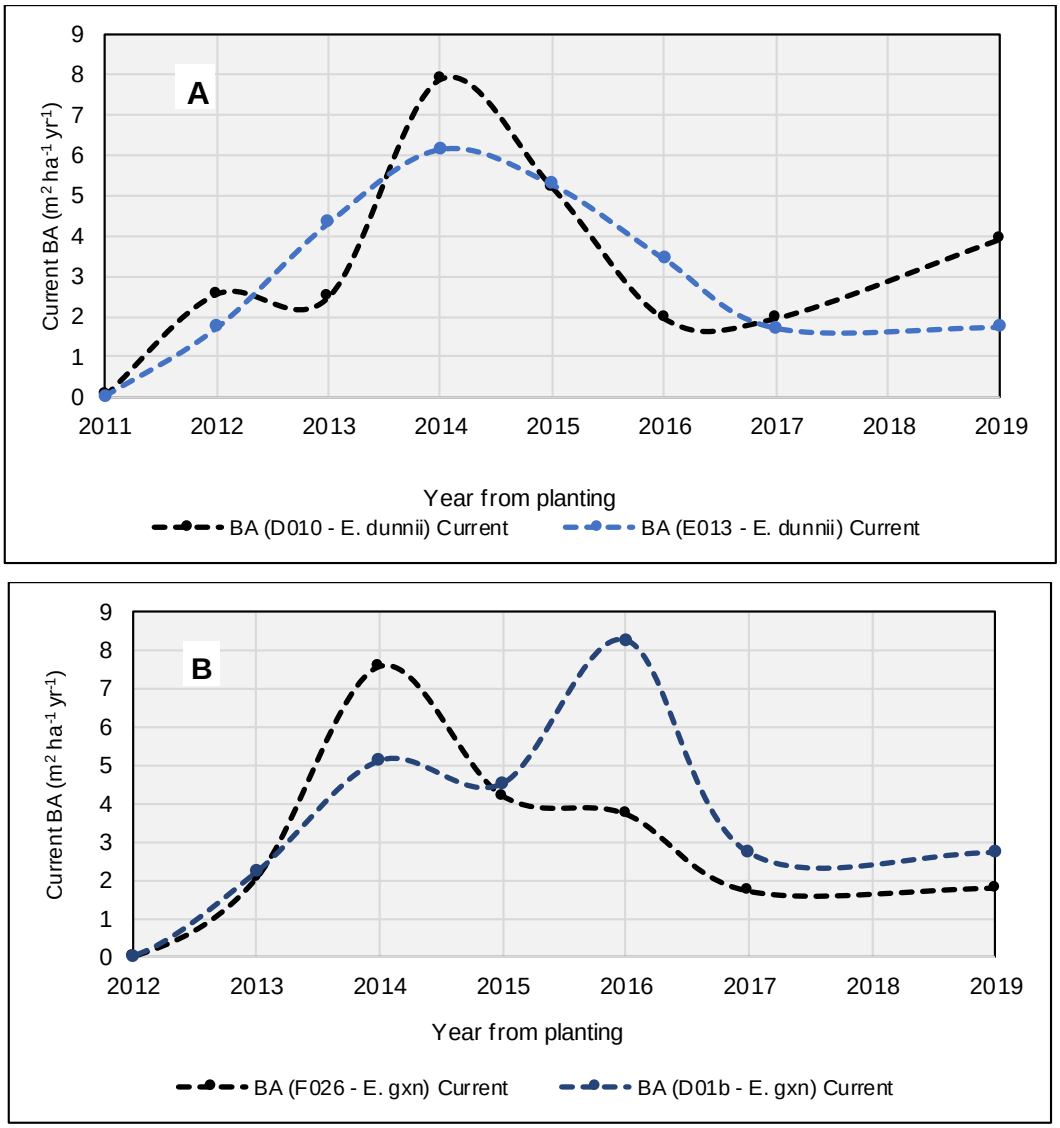

Figure 4.78 A & B: Current basal area increment grouped by genotype across 4 experiments. *E. dunnii* trials (Figure 4.78A) were established in 2011 and *E. gxn* trials (Figure 4.78B) in 2012

In summary, both *E. dunnii* experiments recorded peak current BA increments coinciding with higher WD levels (Figure 4.77A). In *terms* of *E. gxn* experiments, trial F026 reached a peak annual BA at an earlier stage (medium productivity site) but decreased rapidly thereafter. The second *E. gxn* trial (D01b) achieved a peak annual increment at 4 years (high productivity site) (Figure 4.78B) but decreased to levels slightly better than trial F026. In general terms, neither of the *E. gxn* clonal sites experienced water deficits as severe as *E. dunnii* experiments yet their current BA increments were never superior (Figure 4.78A, Figure 4.78B). Cumulative basal areas were closely contested across genotypes (Figure 4.79) with 3 of the 4 trials, exception of F026, revealing comparable BA at trial termination. It is acknowledged that there were differences in establishment dates, but this was

accounted for in current basal areas comparisons (Figure 478A, Figure 4.78B). Importantly, the trend of cumulative basal areas pointed to the ability of the drought tolerant *E. dunnii*, which had experienced a much more severe WD in 2015, to more efficiently exploit scarce soil water as opposed to the clonal counterpart.

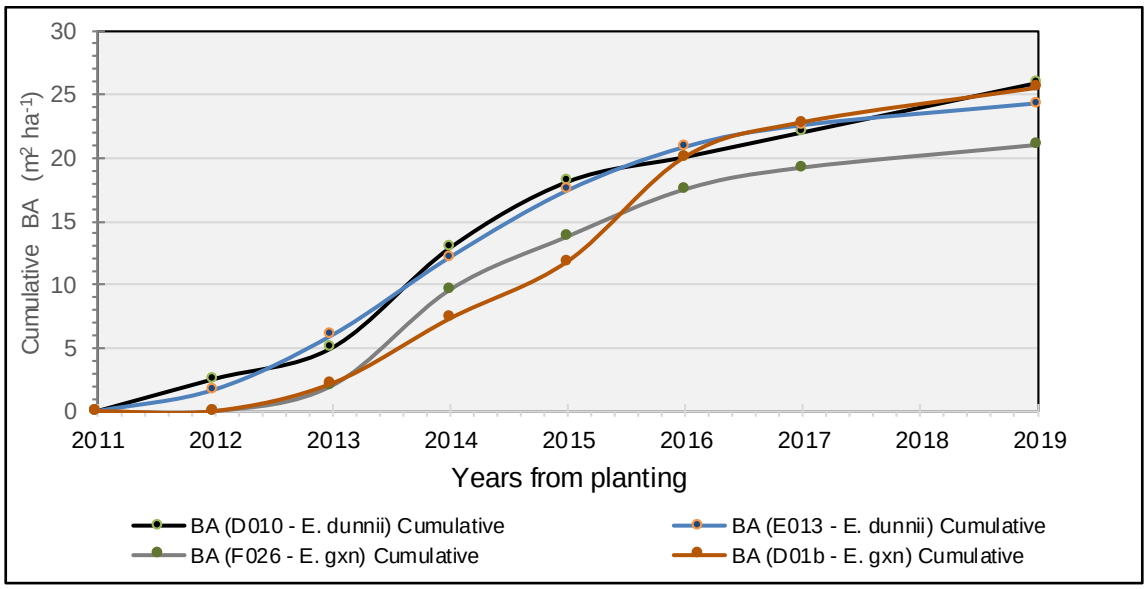

Figure 4.79: Cumulative basal (m^2 ha^{-1}) across all 4 experiments. Cumulative basal areas were comparable for 3 of 4 trials (exception of F026 – lowered survival) whilst water deficits were much more pronounced for *E. dunnii* sites

4.15.4. MAIN AND INTERACTIVE EFFECTS OVER TIME - COMBINED TRIALS

Main factors, site, residue management, RPV, nursery hardening and insecticide accounted for 81% of differences by 394 DAP (1 year) with site and residue management each accounting for 30% of differences in BA whilst RPV = 14%. At 734 DAP, site accounted for 74%, decreasing to 40% at 3011 DAP (Appendix 3). Site fertility for all four trials was generally comparable; however, differences in plant available water did exist (Table 4.14). The impact of residue management decreased rapidly from 734 DAP to account for only 1% of BA differences by 3011 DAP. Nursery plug volume (RPV) declined from 14% of BA variance at 394 DAP (≈1 year) to 3% at 3011 DAP (Figure 4.80). This illustrated the early importance of growth to nursey plug volume, but this influence decreased rapidly thereafter. The insect factor (application or no application of insecticide treatments) accounted for only 0.25% at 394 DAP but increased to 5% by 3011 DAP (≈8 years) at rotation end.

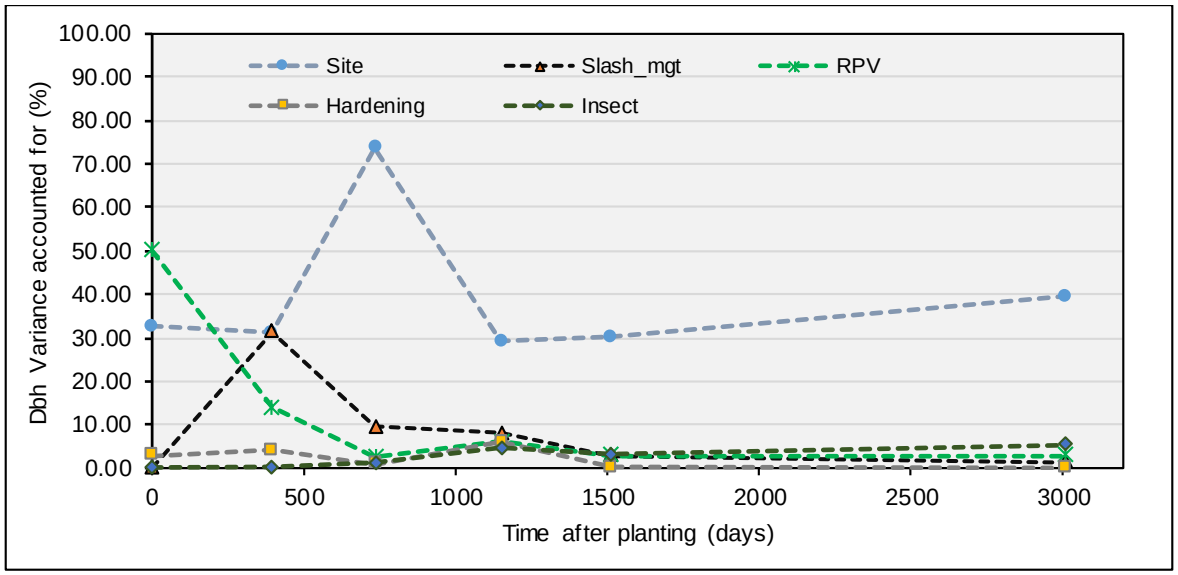

Figure 4.80: Grouped trials - Variance accounting for BA - Main effects

Factor interactions recorded very low values (< 4%) from 394 – 1512 DAP in accounting for differences in BA. At 1512 DAP the best performing factor interactions, 1) site x residue management x insect, 2) Residue management x hardening x insect accounted for 5% of variance in BA, whilst by 3011 DAP, RPV x hardening was the only noteworthy treatment interaction explaining 9% of variance in BA. This figure doubled from 1512 DAP (4% to 9%) to 3011 DAP (Figure 4.81).

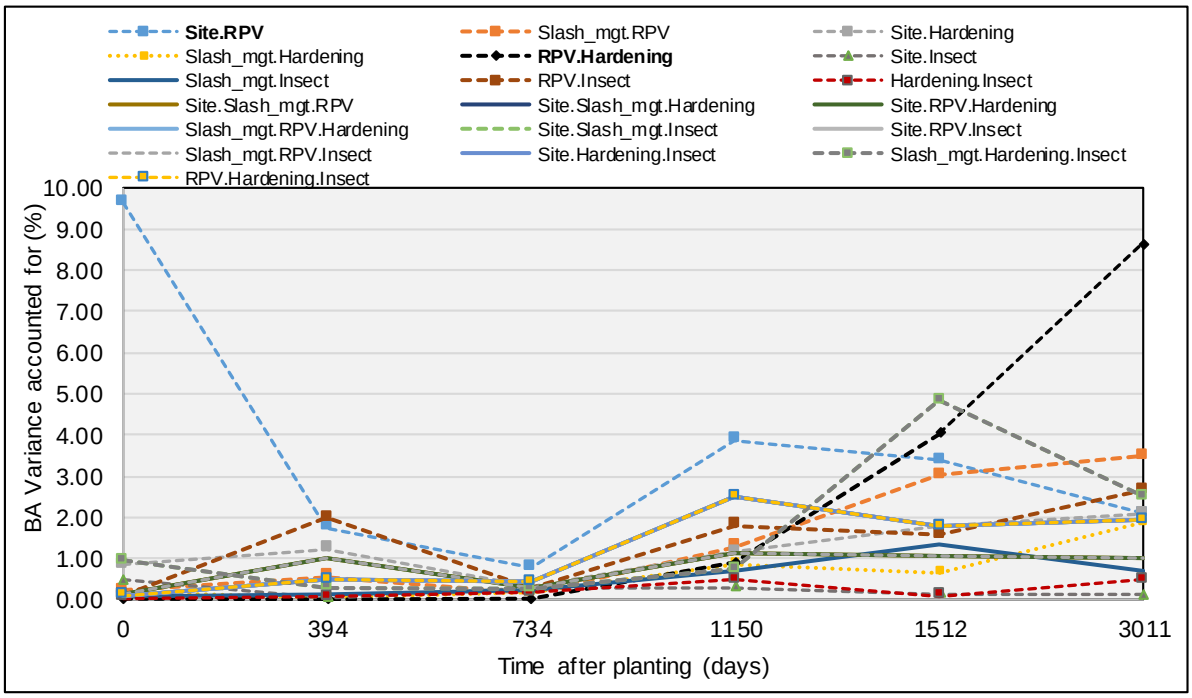

Figure 4.81: Grouped trials - Variance accounting for BA – Interactions

4.15.5. ABSOLUTE AND RELATIVE DIFFERENCES ACROSS COMBINED TRIAL DATA

Absolute and relative differences were interrogated to identify where variability within mean BA was concentrated. For the combined trials (2 x *E. dunnii;* 2 x *E. gxn* trials), mean BA for the residue management treatments showed weak Type 2 growth responses, with burning producing the highest mean BA values from 3 months through to full rotation. Absolute BA differences between residue management treatments were minor at full rotation with burning = 24.3 m^2 ha^{-1}, mulching = 24.2 m^2 ha^{-1} and spread slash = 23.8 m^2 ha^{-1} (Figure 4.82). Root plug volume (RPV) was consistently superior for the large plug cavity volume (105 cm^3) from 1150 DAP. By full rotation, the large plug (105 cm^3) = 24.52 m^2 ha^{-1} whilst the standard plug (60 cm^3) = 23.92 m^2 ha^{-1}. In summary, a large plug volume (105 cm^3) produced a higher mean BA for both *E. dunnii* trials and a single *E. gxn* trial.

The nursery hardening protocol reversed expected BA gains. At full rotation the hardened and unhardened treatments were close to equal at 24.2 m^2 ha^{-1}. Absolute differences between hardening treatments of plant stock revealed minor gains up to full rotation where no hardening was applied, reaching a maximum range = 0.05 m^2 ha^{-1} at full rotation. Results indicated that response to hardening would appear to be genotypically responsive but of little consequence at the grouped level. The insecticide factor (insecticide vs. no insecticide application) showed no differences in mean BA up to 3 years. Thereafter, insecticide treated plots showed positive BA gains up to full rotation (no insecticide = 23.8 m^2 ha^{-1}; insecticide = 24.6 m^2 ha^{-1}) and absolute BA gains responded strongly to insecticide treatment. (Figure 4.82).

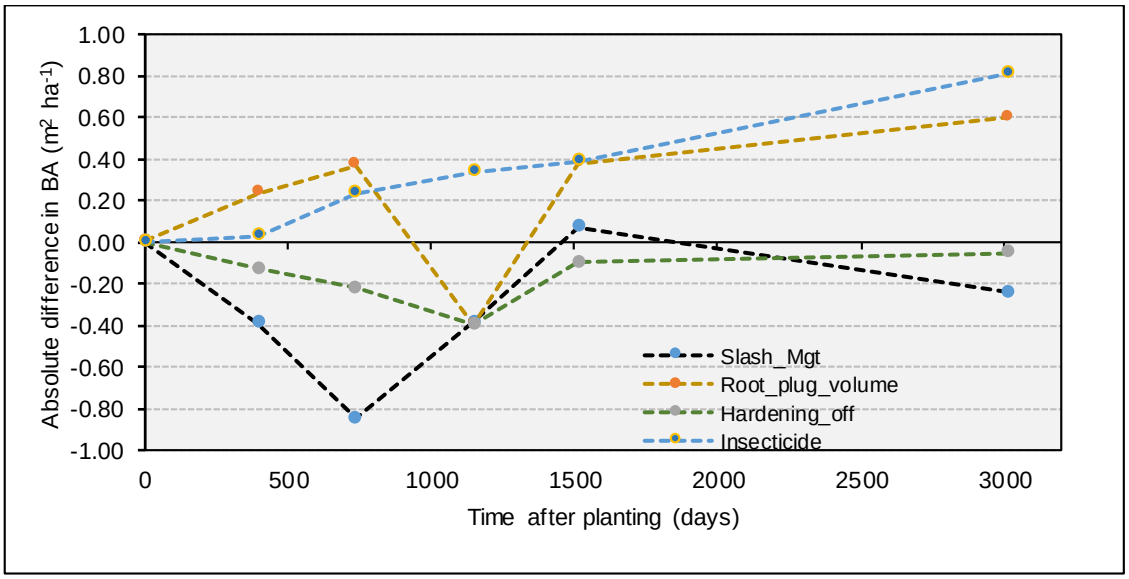

Figure 4.82: Grouped trials: Absolute differences for BA (m^2 ha^{-1}) from 0 - 3011 DAP 1). Burn – mulch, 2). Root plug volume (105 cm^3 – 60 cm^3) 3). Hardening of plant stock minus non-hardening 4). Application of insecticide minus no application

4.15.6. COMBINED TRIALS RELATIVE DIFFERENCES – BASAL AREA

Relative differences (absolute differences divided by standard treatment) in mean BA between burning and mulch showed initial gains up to 1100 DAP but these dissipated thereafter (Figure 4.82). Root plug volume (RPV) revealed an early increase (0.20 m^2 ha^{-1}) at 3 months but declined to zero by end of the trials. Increases in BA were more specific at the individual trial level. Early RPV (1 to 3 years) was strongly influenced by genotype but disappeared at full rotation. Small relative gains accrued by **not applying nursery hardening** up to 394 DAP, but thereafter were negligible for the duration of trials.

In summary, relative differences between silviculture treatments revealed promising early gains from 100 DAP but all declined to around zero by 1500 DAP and remained constant through to full rotation, with BA showing the most response to the individual treatments, RPV and residue management, albeit slight (Figure 4.83).

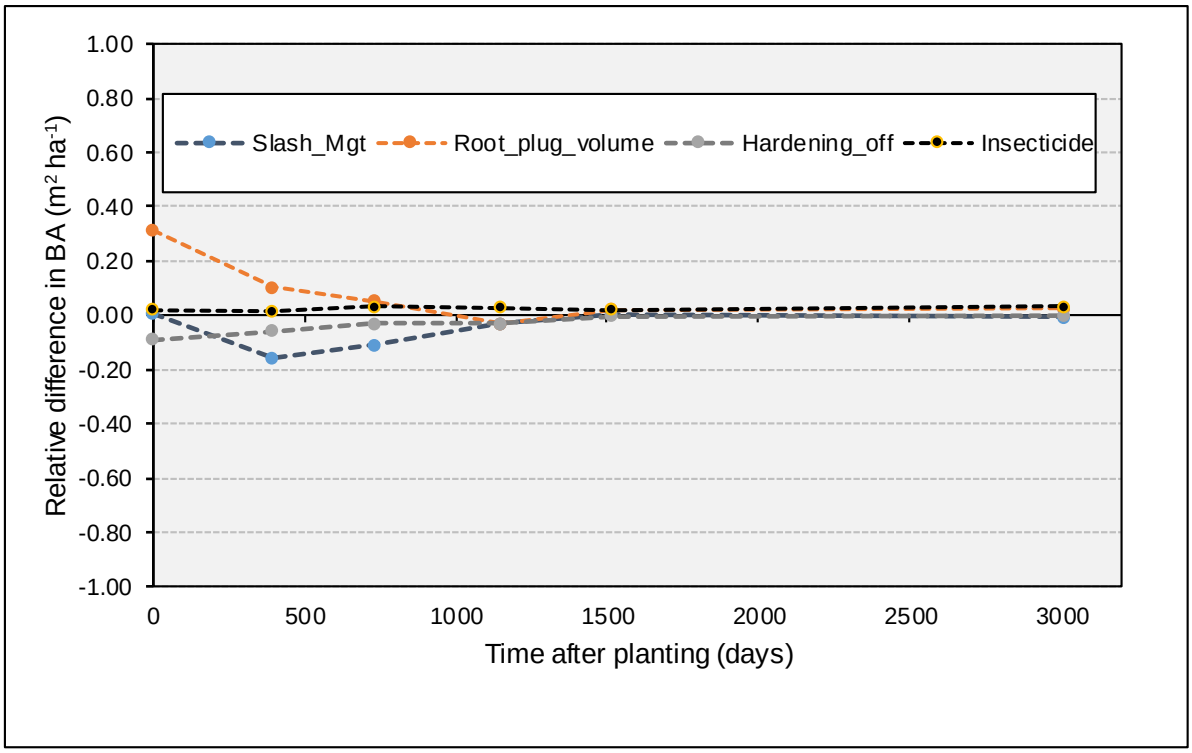

Figure 4.83: Grouped trials: Relative differences for BA (m^2 ha^{-1}) from 0 – 3011 DAP 1). Slash Mgt - Burn – mulch diff. 3). Root plug volume (105 cm^3 – 60 cm^3) 4). Hardening of plant stock 5). Application of insecticide vs. no application

CHAPTER 5: DISCUSSION

INTRODUCTION

Continuous improvements in eucalypt productivity have been observed through the deployment of improved genotypes and implementation of appropriate site management practices (Gonçalves *et al*., 2013). Operational gains must incorporate site species matching, robust planting stock, minimum tillage cultivation, planting density, weed control, pest management and fertilisation as practices that contribute to the improvement of survival, growth and uniformity, through improved soil water management and drought tolerance (Crous *et al*., 2019; Pallet and Sale, 2002; Du Toit *et al*., 2010). The greatest challenge remains the erratic threats imposed by thermic, hydric and biotic stress over a rotation. Prior to canopy closure, trees are more responsive to silvicultural treatments whereas after canopy closure, intraspecific competition for resources (light and water) becomes stronger in short-rotation eucalypt stands, with peak LAI coinciding with the highest rate of biomass production and evapotranspiration (Ryan *et al.,* 1997; Gonçalves *et al*., 2013; Crous *et al*., 2019). Silvicultural treatments that increase nutrient availability after planting when soil water is not limiting are the most likely to yield the greatest response, if applied under current South African conditions before culmination of leaf area development (Crous *et al*., 2019).

Successful and rapid establishment increases the ability of plant stock to survive under stressful conditions imposed by nutrient deficiencies, moisture deficits and biotic threats, and provides rapid growth (Crous *et al*., 2019). Du Toit *et al*. (2010) adds that interactions and response mechanisms to intensive silviculture are additive when implemented simultaneously and will maximize productivity. Combined good silviculture practices drive initial survival and early growth, whilst volume increment after canopy closure is more a function of plant available water, the ability to survive and rapidly recover from water stress, and the ability of trees to recycle nutrients (Crous *et al*., 2019; du Toit, 2008).

A combination of erratic nursery quality and planting practices has been associated with poor survival and sub-optimal growth in South African eucalypt pulpwood plantations. Research into eucalypt re-establishment practices in South Africa has been inconclusive regarding important re-establishment practices such as 1) pit size 2) application of water at planting 3) planting techniques 4) plant quality and their potential impact on transplant survival and growth (Viero, 2004). This is complicated by the numerous confounding factors across very diverse site types.

Evans (1999) notes that timber plantations have an impact on the sites they occupy and can dynamically, and quite imperceptibly at times, alter the site through their evolving moisture and nutrient requirements. Under certain conditions, nutrient export may threaten sustainability but care with harvesting operations, conservation of organic matter, minimising soil erosion and management of the weed environment are more important to preserve site quality. Plantation forestry appears to be entirely sustainable under conditions of good husbandry, but not so where wasteful and damaging practices are prevalent or overlooked. Huang *et al*., (2008) state that the effect of mulch on the growth of forest plantations has been studied for a number of species and soils; however, our understanding of the physiological mechanisms underpinning the growth response to mulch in hardwood plantations remains somewhat limited. Additionally, the effect of mulch on tree growth varies with soils, taxa, microclimate, mulch type and may differ according to short and medium term weather patterns. Forest residue retention, although an important tool in site sustainability is but one component of a number that are just as critically important. The aim of this study was to determine what the combined effects of site, physiological and morphological effects of harvest residue management, and planting stock size played in optimizing survival, growth and uniformity of trials established in the KZN Midlands of South Africa.

It was postulated in the current study that a simple combination of mulching and larger more robust nursery plants must result in better-stocked and more vigorously growing out-plantings. Although clearly recognised that burning is a valuable and economically viable residue management tool, it should most definitely be augmented with alternate residue management techniques that are equally productive and more beneficial in terms of long-term site sustainability. There is an understandable aversion to mulching due to the high cost; however, experience has shown that there are benefits to be garnered, with fire protection being a potentially strong additional point. The environmental benefits of the technology are far reaching and the potential gains gauged in terms of long time site sustainability. With ever shrinking plantable areas in South Africa, the environmental and legal pressures placed on obtaining water permits for planting, and the growing impacts of climate change clearly upon us, understanding what drives early survival, growth and uniformity at the commercial scale is the cornerstone to our timber industry success. The adage, '*you're only as good as what you measure'* is more relevant than ever before. Through strict independent inventory, companies have begun to audit the impacts of silviculture factors ranging from nursery plant quality, pitting, planting and blanking on tree survival and uniformity.

5.1. UNDERSTANDING THE IMPORTANCE OF SITE WATER DEFICIT

The importance of understanding the water deficit values of the site is critical as opposed to the sole reliance on MAP when determining site-species matching or projecting expected yields. Forest production in regions with a water deficit of more than 400 mm and dry season longer than 6 months, are uneconomical for commercial forestry ventures due to low site productivity (MAI), poor wood properties (high lignin and resin contents) and high inputs costs of silviculture and fire protection (Gonçalves *et al*., 2017). Where high value products are harvested or other economical services are included, such as bee keeping or wind breaks to protect other high value crops, it may become economically viable to plant trees on such dry landscapes (Du Toit, *et al*., 2017). Water deficits (WD) for the four trials were moderate when compared to Brazilian sites (Gonçalves *et al*., 2017); however, temperatures were also lower and hence productivity.

It is important to note that the planting of a different suite of eucalypt species and hybrids also meant a direct comparison with cited literature in Section 4.1 was not possible. Further, winter temperatures in Hilton, KZN drop to 0 °C, resulting in the cessation of productive photosynthesis during the day and biomass productivity ultimately lost. In summary, water deficits (WD as mm y^{-1}) recorded at the study sites, although moderate by South African standards, were still higher than the equivalent Brazilian Köppen Geiger climate type. However, edapho-climatic conditions are different and thus could not predict MAI, especially as Brazilian forestry sites receive a high mean annual rainfall (MAP as mm y^{-1}). Experiment results placed water deficit results in perspective and were moderate by both Brazilian and South Africa standards. There was a linear relationship (Figure 4.3) between water deficit and height growth for the four experiments and this reinforced the importance of a site index based on dominant heights.

5.1.1. THE RESPONSE OF GENOTYPES TO WATER DEFICIT

Trend lines plotted for height over trial rotations highlighted differences between genotypes, with *E. dunnii* only slightly affected by a 10 mm increase (Figure 4.5) in water deficit, whilst *E. gxn* was more sensitive to a similar increase (Figure 4.5). Annual water deficits for the *E. dunnii* experiments reached a peak of close to 200 mm y^{-1} by 48 months (Figure 4.5), decreasing to less than 50 mm y^{-1} at full rotation. Conditions were generally very favourable for growth but this was not reflected in equable tree mortality across all experiments with a single *E. gxn* (Site F026*)* recording the highest mortality, most likely as result of the onset of intraspecific competition. Although cumulative basal areas (Figure 4.79) were

comparable, there were different responses in terms of current basal areas (Figure 4.78) with a peak achieved across all trials at 3 to 4 years and thereafter a rapid decline.

The variation in production between *Eucalyptus* clones has been recorded to be lowest on poor sites, suggesting that a strongly limiting factor such as water supply, or a high water deficit, limits the expression of genotypic differences and therefore the greatest gains for improved genetic material can only be realised when established on sites with high production potential (Binkley *et al.*, 2013; Crous *et al.*, 2019). Based on cited literature and trial data from the water deficit study, a conceptualisation was elucidated to explain (Figure 5.1), where under favourable soil water conditions, an *E. gxn* clone would outperform the *E. dunnii* seedling in terms of total biomass production, specifically wood fibre (Figure 5.1 – red line) in line with Crous *et al*. (2019), who state that some genotypes have a competitive advantage and are able to more effectively utilise site resources on a specific site. Results from a plot of cumulative basal area (Figure 4.79) support the conceptualisation in Figure 5.1.

Commercial clonal programmes generally focus on selections based on highest volume yields and tend to be quite site specific with Crous *et al*. (2019), citing Meads (2005), reporting up to a 20 fold difference in performance between poorest and best performing species. In terms of an orthodox breeding strategy, this is a sensible approach ensuring that industrial eucalypt plantations remain highly productive. By comparison, the more generalist-performing seedling selections such as *E. dunnii,* with their known drought tolerant properties are planted to more marginal sites, with expected lower stand volumes (Figure 5.1 - green line). It was postulated that as soil moisture becomes limiting (increased water deficit) clonal growth performance rapidly declined, compared to the more drought tolerant *E. dunnii* counterpart. Where factors such as site and climate are limiting, the full realised benefits of tree improvement and intensive silviculture will not be realised (Crous *et al*., 2019). Such situations have occurred in Zululand during the drought of 2014 and low rainfall of 2015 in the KZN Midlands (Table 4.14).

Results reported under Section 4.15.3 (The Impacts of Water Deficit on Basal Area) showed evidence to support this diagrammatic conceptualisation (Figure 5.1). At increasing days after planting (DAP), and under similar water deficit ranges (Figure 4.77A, Figure 4.77B), the *E. gxn* clone produced a lower BA (Figure 4.78B) and was evident that the clone required wetter site conditions (lower WD) to produce a BA equivalent to *E. dunnii*. It is also worth considering the issue of biomass allocation to branches in moderately cold tolerant hybrids thus resulting in a lower allocation to BA. The inherent ability of *E. dunnii* to deal

with high water deficits is impressive and points to the drought resilience of the species or possibly the ability to tap soil water sources at great depths. Genotypes with low LAI tend to have high root area index to leaf area index ratio and larger fine root biomass compared to less drought tolerant genotypes. This allows a greater investment in root carbon, improving drought avoidance strategies (Pinheiro *et al*., 2016; Hakamada *et al*., 2020).

It is acknowledged that the four data sets provided limited data to support the hypothesis (Figure 5.1). From the height growth data (unaffected by stocking), it appeared (Figure 4.3) to roughly support the hypothesized graph (Figure 5.1). It would appear that most responsive genotypes (selected for volume production) reward the grower when deployed on sites with low water deficits (Figure 4.79). In the warm temperate areas of KwaZulu-Natal, BA differences between eucalypt species range from 3 to 12 fold with the best genotypes outperforming the trial mean by 62 % (Crous *et al*., 2019). Under conditions of higher water deficit, *E. dunnii* showed a flat growth trend. However, the conundrum remains that clones are normally deployed on better sites whilst *E. dunnii* is planted on more marginal drought susceptible types, making it difficult to thoroughly test the hypothesis. Further experiments where each genotype is tested across a very wide range of water deficits will be required to test the hypothesis more rigorously.

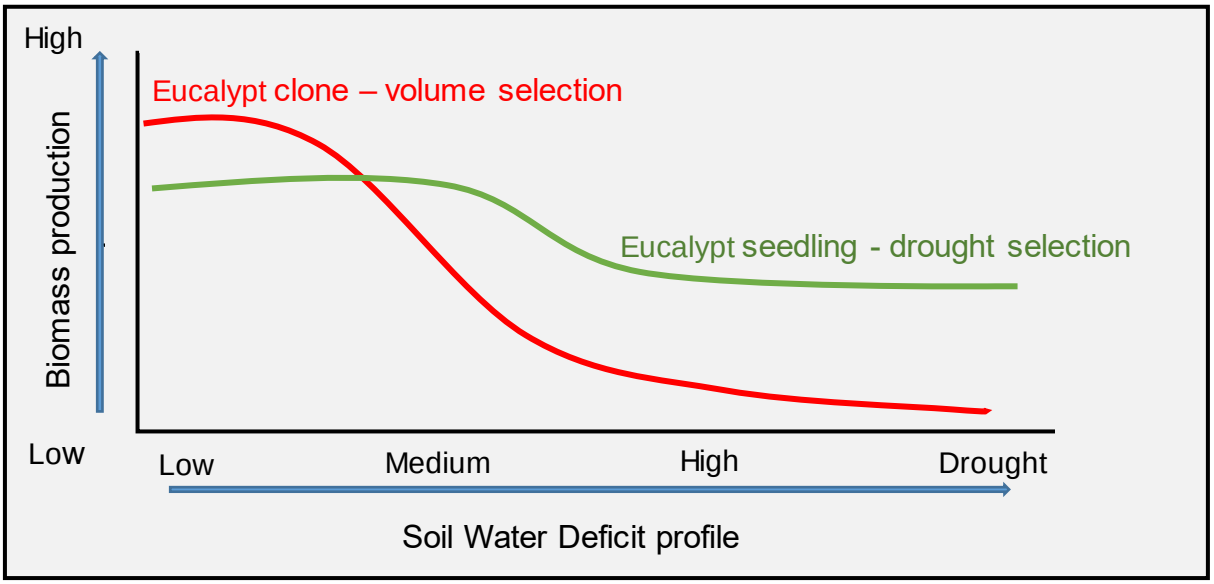

Figure 5.1: Schematic representation of biomass production responses to water stress in eucalypts

Results showed that stocking decreased across three of four trial sites. Reasons for such mortality could not be directly attributed to a specific abiotic or biotic stressor. Factors such as plant quality and silviculture inputs were equal and thus more likely that stocking was

under pressure during the final year of rotation due to the impact of strong intraspecific competition; however, Crous *et al*., (2019) state that growth differences between sites reported on are generally much greater than that of the treatments tested within sites. The size density relationship was considered where trees of greater size compete more intensely and maximum stocking for a site strongly is dependent on tree size and generally agreed with the findings of Curtis (2012).

In terms of the experiment series, most sites were in the fully stocked zone by 99 months (Refer to Tables 4.17 and 4.18). Under such circumstances, tree mortality had commenced, and one site (F026) was characterised by multiple and scattered windfalls even though site conditions in terms of a low WD and soil fertility were favourable. It is worth considering that the RD threshold values for clonal *E. gxn* could be less than 12 due to the adventitious root type (Figure 2.5). Such hybrids tend to colonise at a shallower depth with root growth more limited to the top 40 cm (Hoffmann *et al*., 1978) of soil making them potentially more susceptible to toppling or a decrease in WD over consecutive years. The exact cause of increased mortality towards rotation end was therefore less likely attributable to an increased water deficit (Figure 4.5) but rather an increase in stand relative density. If this assumption is correct, it may also explain why the high WD by mid rotation did not kill trees. Simplistically stated, trees were too small at this stage to be under severe intraspecific competition or alternatively, water deficits were never extreme enough to kill trees outright and mortality at rotation end was due to non-water related causes.

As we experience further climate change, weather patterns will become increasingly unpredictable, expressed through declining total MAP, or monthly rainfall distribution. It will become increasingly critical to review our yield expectations for South African industrial eucalypt plantations. This will require a reassessment of site x genotype matching and the development of breeding strategies and silviculture practices that enable more resilient plantings with greater emphasis on survival and uniformity. It is likely that future yields will remain static or slightly increases as a result of effective breeding and site species matching, but to avoid significant drought damage, the adoption of breeding programmes will be essential as every industrial eucalypt planting in South Africa will experience at least one major drought event during a full rotation.

5.2. THE IMPORTANT ROLE OF PLANTING STOCK

Hechter *et al.* (2018) record that nursery plant quality and planting practices in South Africa have created a set of interactive factors that make it very difficult to interpret which factor in

the combination is most pronounced. During periods of prolonged water stress, larger prime plants, planted deeply, with the addition of water, ensure optimal survival and growth. Certain attributes quantifying morphological plant quality maybe grouped into physical and performance categories (Mattsson 1997). Physical attributes consist of factors such as morphology, bud dormancy, water status and nutrition, whereas performance attributes comprise frost hardiness, growth vigour and root growth potential (Mattsson 1997). When assessing plant quality, morphological characteristics are the first considered due to their ease of measurement (Maclennan and Fennessy 2006), and include age, height, root collar diameter, bud length, shoot: root ratio, shoot weight and root weight and nutrition (Sutton 1979, South and Mitchell 2006). MacLennan and Fennessy (2006) report that plant quality should be determined by the intention of its use whilst Ritchie (2003) best describes plant quality as the fitness for purpose. This study strongly supports both these statements as root plug volume and conditioning of nursery stock positively affect basal area at varying stages in the rotation of industrial short rotation eucalypts.

Poor survival and early growth have profoundly detrimental effects on final yield, associated with poor site-species matching, inferior nursery stock, substandard silvicultural practices, marginal planting sites and soil moisture status (Squire,1977; Flinn, 1978; Burdett, 1990; Neary *et al*.,1990; Malan, 1993; Morris, 1994; Zwolinski *et al*., 1995; Darrow, 1995; Mattsson, 1997; Turvey, 1996; Stape *et al.,* 2001; Campbell and Hawkins, 2004; Close *et al*., 2005; Thomas, 2008). The impact of poor plant quality and planting practices, when combined with adverse environmental conditions (phenological responses) undermine survival and growth and negatively affect the potential of young trees to exploit fully site resources (Nambiar *et al*., 1979; Tear *et al*., 1982; Ellis, 1995).

Trial results for this report confirmed the importance of plant quality but planting depth, residue management and the application of insecticide are all of importance at differing times and within interactions over the full rotation period. Although not part of the study, it is more practicable to plant larger nursery stock deeper than a smaller equivalent without a negative impact on the above ground shoot length (Rolando and Little, 2009). Brady and Weil (1999) report that there are definite benefits to deeper planting, especially during water shortages as the upper soil levels tend to dry out rapidly. Deeper planting with large plants also allow roots to access soil moisture and encourages improved growth (Crous 2016).

Root plug volume (RPV), as tested in the experiments, played a pivotal role in nursery stock robustness with research showing that post-planting survival and subsequent growth improvements by establishing large primed plants as compared to smaller primed

counterparts (Grossnickle 2005). Trial conclusions supported these statements with gains in Gld/Dbh and basal area contributing to superior early growth. Root plug volume (RPV) in the grouped trial series consistently favoured the large plug cavity volume (Figure 4.80). At full rotation the large plug (105 cm^3) = 24.5 m^2 ha^{-1} whilst the standard plug (60 cm^3) = 23.9 m^2 ha^{-1}.

Absolute differences did identify plug volume (RPV) and nursery hardening as positive contributory factors to early Dbh and hence basal area gains (Table 4.30). By 36 months only plug volume (RPV) and the application of nursery hardening as main effects were still significant. At 48 months main factors (RPV, hardening, residue management, and insecticide) ceased to explain mean variance in BA across all trials and by full rotation, BA differences were only explainable in terms of site, and to a lesser degree, the combination of plug volume and hardening. However, mean square (ms) values indicated that site differences explained 40% of basal area variability whilst the interaction of plug volume and nursery hardening could only account for 9% of BA differences in the combined analysis (Figure 4.81). The experiment site with the lowest water deficit (Site D01b) planted to a responsive clone showed significant improvements to the standard plug exposed to hardening in the nursery.

In summary, basal area differences were mostly explainable by site variability and to a lesser measure nursery practices, but silviculture factors such as insecticide applications and residue management were not significantly different by rotation end in the combined analysis**.** Crous *et al.,* (2019) state that growth differences between sites is of much greater importance than that of treatments tested within sites and also revealed that superior silviculture only increased basal area by 5% at full rotation. Their respective early roles diminish towards final rotation and must always be regarded as part of a total silviculture establishment 'package' of additive effects and not a single main effect(s) that individually drives superior survival, growth and uniformity. Morris (2008); Gonçalves *et al*. (2013); Harwood and Nambiar (2014), Crous *et al.*(2019) all state that plantation productivity gains are not related to a single silviculture treatment, but require the application of integrated management.

Although correlations between nursery plant volume, survival and growth exist, soil moisture remains the single most important driver affecting transplant mortality (Grossnickle 2005). Water stress at planting is regarded as one of the major reasons for hydraulic shock which manifests as insufficient root-to-soil surface contact, thereby significantly increasing the potential for mortality (Burdett 1990; Viero, 2019). Transplant stress can be ascribed to the

inability of roots to access available soil water and it is critical that adequate soil water be applied timeously to improve survival following planting (Kozlowski and Davies, 1975; Burdett, 1990). The period at and immediately after planting is absolutely critical where a consolidated and saturated root plug plays an important role in improving initial transplant survival (Grossnickle 2005), highlighting the importance of using a fully hydrated root plug at planting (Viero, 2019).

It is well documented that active root growth is essential for good post-planting survival and for this to occur; the physiological processes required for phenological development must be facilitated (Sands 1984; Brissette and Chambers 1992; Viero 2019). There are very few recent studies where the combined effects of RPV and nursery hardening on planting success have been examined (Davis and Jacobs 2005). Studies to date show that root system attributes such as larger consolidated root volumes, high root fibrosity and an increased number of first order lateral roots benefit improved field performance (Davis and Jacobs 2005). Eucalypts display dimorphic responses in that they possess widely spreading lateral roots just below the soil surface and a deep taproot system in young trees that develops deep sinker roots as trees mature (Knight, 1999). Such roots are defined as opportunistic and follow gradients of increasing water availability. Mechanisms that enable a eucalypt clone to cope with periodic and severe water deficits in the soil will inevitably result in a trade off in terms of reduced growth potential and expressed by a root:shoot ratio ranging from 0.8 – 0.12 (Gonçalves *et al.,* 2017).

Results from ICFR trials illustrate that overall survival for larger prime plants (72 cavity polystyrene tray = 103 cm^3 volume $cavity^{-1}$) was higher than smaller prime plants (128 cavity polystyrene tray = 36 cm^3 volume $cavity^{-1}$). Planting larger plants, deeper into the soil resulted in improved basal area and tree volume across all sites, suggesting that larger primed plants better tolerate a wider range of variable site conditions. On sites that received high rainfall before and after planting, any treatment interaction between deeper planting and applying water can be masked (Hechter *et al*., 2018). The combination of favourable edapho-climatic conditions will often conceal the impact of silviculture treatments as shown in the experiment series.

Although plug volume and nursery hardening were shown to be statistically significant in their overall impact on Gld/Dbh and basal area at specific times of measure, their absolute and relative gains were less than anticipated where inherent site qualities were good and soil moisture not limiting and thus intraspecific gains were nullified by full rotation. These findings are support work by Du Toit and Dovey (2005); Du Toit (2008); Du Toit *et al*. (2010),

as cited by Crous *et al*. (2019). Experiment results presented in this thesis showed that response to hardening would appear to be genotypically responsive but of little consequence at the combined level. The insect factor (insecticide vs. no insecticide application) showed no differences in mean BA up to 3 years, where-after insecticide applications showed positive BA gains (Figure 4.83) up to full rotation.

5.3. ACCOUNTING FOR DBH AND BASAL AREA DIFFERENCES IN THE TRIAL SERIES

Basal area as an accurate predictor of forest dynamics is a reliable tool for growth and yield modelling. It can determine more than just stand density and is the cornerstone for important forest management decisions (Murphy and Shelton 1996; Chen *et al*., 2007; Elledge and Barlow, 2012). Chukwu *et al*. (2018) state that basal area (BA) is an important characteristic in defining the amount of area occupied by a tree stem, or more correctly the total cross sectional area of all stems in a stand measured at breast height per unit area of land.

5.3.1. HIGH PRODUCTIVITY SITE (TRIAL D010 – *E. DUNNII*)

Main factors accounted for 56% of Dbh variance by full rotation (Figure 4.6). The only interaction able to account for variance was residue management x plug volume (< 20% of BA at 2 years of age) but decreased to less than 8% by rotation end (Figure 4.7). Soil water availability is assumed to have played a major role (Figure 4.77; Figure 4.78). Crous *et al.* (2019), reporting on a series of similar trials found that significant interactions between treatments were absent. Although this site received a high productivity rating due to a predominance of deeper soils, certain parts of the trial site were shallow and susceptible to high water deficit.

5.3.2. MEDIUM PRODUCTIVITY SITE (TRIAL E013 – *E. DUNNII*)

Main factors accounted for 90% of early Dbh differences, with plug volume accounting for only 10% at full rotation. Residue management accounted for 58% of Dbh variance in the first year but declined rapidly by rotation end, possibly due to high water deficits during years 4 and 5 (Figure 4.11). Growth variability in response to residue management revealed an initial Dbh increase on burn sites, a response to bio-available nutrients (base cations), whilst mulch and spread residues were in the initial phases of decomposition and likely drawing down on available N. With time, all three residue treatments would become less influential in driving Dbh variance and hence a decline in the impact of residue management accounting for variation in Dbh by full rotation.

As opposed to the high productivity site (D010), the medium productivity (E013) site revealed two interactions 1) Residue management x hardening and 2) Plug volume x hardening that accounted for 14% and 13% of BA variance respectively. Results consistently reflected the significance of hardening of planting stock in the nursery and its impact on a number of treatments results up to full rotation (Figure 4.12).

5.3.3. MEDIUM PRODUCTIVITY SITE (TRIAL F026 – *E. GXN*)

Main factors accounted for 41% of differences in Dbh at rotation end with rep accounting for 24% of total variance. Residue management and RPV would jointly account for 10% of variance in Dbh at full rotation (Figure 4.13) whereas hardening spiked at 23% at 3 years, declining to 1% at 7 years (Figure 4.13). In terms of interactions, only RPV x hardening x insecticide application accounted for 13% of Dbh variance at rotation end (Figure 4.14 - Brown dotted line).

Main factors were responsible for 48% of BA variance, with rep accounting for 21% of BA variance at rotation end with residue management and plug volume = 13% at 7 years (Figure 4.15). Nursery hardening accounted for 10% of BA variance at full rotation. The medium productivity site showed a single interaction of RPV x hardening x insecticide accounted for 16% of BA variance at full rotation (Figure 4.16), reinforcing that the response to intensive silviculture is largely additive (Schönau 1989; Mead 2005). It is important to note the trend of stocking to site fertility and water deficits, it the gradual decrease across all four experiments. Stocking declines for three of the four trials all followed similar low mortality rates (mean = 1533 Spha across three trials) through to full rotation (Figure 4.5). However, mortality at Site F026, *E. gxn*, was higher, decreasing to 1439 Spha at 12 months. Reasons for mortality were definitely not biotic. Factors such as plant quality and silviculture inputs were exactly as for Trial D01b. It is quite clear that stocking was under pressure during the final year of rotation due to intraspecific competition. To explain this more precisely, the size density relationship was considered whereby trees of bigger size compete more intensely and maximum stocking of a site is therefore strongly dependent on tree size (Table 4.17). Rooting depth and wind exposure may also have contributed to windfall damage in this trial.

5.3.4. HIGH PRODUCTIVITY SITE (TRIAL D01B – *E. GXN*)

All the main factors, residue management, RPV, hardening and insecticide showed negligible impact (14%) on Dbh variability by full rotation. The additive effects (Schönau 1989; Mead 2005; Du Toit et al., 2008) were more apparent with 1) residue management combined with hardening, and 2) RPV combined with insecticide both accounting for 27% of Dbh variance at full rotation (Figure 4.19). Two treatment interactions accounted for basal area variability, 1) residue management x hardening at 3 years (15%) and 2) plug volume x hardening from 4 years to full rotation at 26%. Where interaction effects were strong, accounting for more than 25% of BA variability (Figure 4.18), final volume was high, with the medium productivity site = 148 m^3 ha^{-1} and high productivity site = 211 m^3 ha^{-1}.

5.4. TRIAL RESPONSES TO SILVICULTURE PRACTICES

The size of trial data sets limited reporting to specific periods; namely, two weeks after planting, at 12 months and final rotation. At each period, only statistically significant scores at 5% and 10% levels were discussed.

5.4.1. EARLY TREATMENT RESPONSE – *E. DUNNII* - HIGH PRODUCTIVITY SITE (D010) - 2 WEEKS POST PLANTING (14 DAP)

Experiment measurements at 14 DAP were recorded to confirm that treatments dating back to the nursery (nursery hardening and RPV) influenced different plant types / morphologies (Table 4.19). Field conditions did not yet impact on growth, although it was likely to have started affecting survival at 14 DAP. At time of planting, nursery transplants only differed due to the application of hardening to two root plug volume (RPV) types at what was referred to as Time 0 (14 DAP). Field conditions on the day of plants of three experiments (Sites D010, D01b and F026) were very favourable; however, Site E013 was planted on a particularly hot day (34 °C). Although such conditions were predicted to cause planting mortality for the experiment, survival for *E. dunnii* seedlings was high.

At 14 DAP, the only possible treatment that may have had an impact, albeit positive, was the insecticide application at planting followed by a second application 12 days later, i.e. 28 DAP. This was supported by burn and residue spread treatments showing significant differences ($p < 0.05$) when treated with insecticide, with the burn and insecticide treatments performing best overall.

5.4.2. TREATMENT RESPONSE – *E. DUNNII* (D010) HIGH PRODUCTIVITY SITE AT 12 MONTHS

F – Prob values at 12 months after planting showed much stronger responses for main silviculture treatments and their interactions (Table 4.21). Although canopy closure did not occur until 15 months for *E. dunnii* trials and 18 months for *E. gxn* trials, 12 months is regarded as an operational threshold when no further silviculture interventions can mitigate poor stocking, uniformity or growth. The benefits of a large plug volume that had undergone hardening should have still been apparent at this stage and physiological measures of stomatal conductance and chlorophyll content indicative of the general vigour of the plantings. Height at 12 months after planting showed significant differences for residue management and the interaction of residue management x plug volume. At 12 months, plug volume (105 cm^3 vs 60 cm^3) could not fully explain mean height differences, whilst residue management, specifically burning, showed the best height performance.

Survival at 12 months was only significant for the interaction of RPV x hardening (Figure 4.23, Table 4.21). A large plug combined with hardening produced the highest survival at 12 months (1644 spha), whilst the lowest survival was for a standard plug exposed to nursery hardening (1582 spha) (Figure 4.23). At 12 months, the burn treatment expressed the best basal area for both plug volumes (large plug = 2.9 $m^2\ ha^{-1}$ and standard plug = 2.7 $m^2\ ha^{-1}$), mostly probably as a response to the nutrient rich environment following burning. Such a response does not necessarily translate into the highest volume at full rotation. Once the biogeochemical cycle is triggered at canopy closure and more specifically maximum LAI, sloughing of bark, die-back of fine branches (cladaptosis) and leaf fall start to provide a greater degree of self-sustaining nutrition on inherently more fertile sites (Bouillet et *al*., 2000; Du Toit, 2008; Gonçalves *et al*., 2000; Gonçalves *et al.,* 2008; Laclau, 2001).

Crown diameter at 12 months was important as the earliest stomatal conductance and chlorophyll content index (CCI) readings could be reported simultaneously (Table 4.22). Of the four trials, two *E. dunnii* trials and one *E. gxn* trial (F026) showed significant differences at the 5% level for crown diameter. It was assumed that the larger the crown diameter, the greater the overall vigour and growth as a function of greater photosynthetic area. Du Toit (2008) states that as a stand develops leaf area, soil water (Figure 4.5) will increasingly constrain resource use efficiency as the stand is able to transpire at the maximum rate. Canopy diameter responded positively to burning, most likely due to stimulated growth in the presence of freely available nutrients, whilst mulch and spread residues showed no significant differences. It would therefore appear that trees responded by deploying a greater leaf area in the burn treatments, with less pronounced (or even insignificant)

changes to photosynthetic efficiency. Du Toit (2008), who records the exact same response for the Karkloof trials, where changes in LAI dominated over changes in canopy quantum efficiency supports these findings.

Stomatal conductance was weakly significant for the factor plug volume at 12 months (Table 4.23) with the larger volume of 105 cm^3 revealing a higher degree of conductance. The effects of hardening of plant stock in the nursery dissipated by 12 months with no significant impact on stomatal conductance. Stomatal conductance measurements as a measure of physiological vigour, from establishment to just before canopy closure were non-significant, possibly as sites only experienced moderate water deficits and strongly seasonal rainfall. Stape *et al.,* (2004) report increased stomatal conductance in eucalypts, post canopy closure, where water is not limiting but such findings were not locally apparent, even though burn treatments did have significantly larger crown diameters and would appear transpire more freely compared to treatments where residues were retained. This may indicate a greater likelihood that progressive hardening or conditioning could be influential in reducing stomatal conductance from a larger crown or that stomatal conductance measurements at one year are masked as canopy closure starts to increase.

RPV x insecticide treatment and residue management x RPV x hardening treatments accounted for significant differences in chlorophyll content index (CCI) at 12 months (Figure 4.25; Figure 4.26; Table 4.24). A combination of a large nursery plug treated with insecticide reflected the most vigour (34.5 units); however, the standard plug x insecticide performed the worst, and hence plug volume would appear more important than insecticide application in terms of overall plant health. At a more complex three-way interaction, a combination of burning x hardening x large plug produced the highest CCI score (Table 4.24) with this positive response possibly linked to the overall growth vigour of trees at 12 months and reduced competition for resources. Du Toit (2008) states that changes in the availability of light, water and nutrients may cause large and significant changes in biomass partitioning to stand components and there is no reason that such resource partitioning at the leaf level do not include the concentration of chlorophyll.

5.4.3. TREATMENT RESPONSE – *E. DUNNII* HIGH PRODUCTIVITY SITE AT FINAL ROTATION (D010)

Mean height at 99 months revealed that a large plug, not exposed to hardening in the nursery performed best (19.8 m) (Figure 4.36), whereas the largest mean Dbh (14.7 cm) was recorded for a large plug planted into spread residues. The role of plug volume and

slash management became increasingly important (Figure 4.38) for tree dimensions over time in this experiment. The highest stocking level reported was for a nursery-hardened treatment x large plug (1605 Spha) and the consistent appearance of plug volume x hardening highlighted that plug volume responded to nursery conditioning right through to final rotation (Figure 4.40).

The application of an insecticide resulted in an increase in BA at full rotation, with large plugs planted into spread residue producing a higher BA than the standard plug counterpart. This was likely due to the early impact of an uneven spread of residues around newly established trees creating a microclimate that may adversely disrupt air movement. Similar conditions are the cause of mortality in specific lines or patterns where harvest residue is stacked during manual harvesting operations, causing both cold and hot air to sink towards adjacent plantings.

Final volume measurements showed significant differences for the application of 1) Insecticide and 2) Residue management x RPV. The application of an insecticide resulted in an increase of 11 m^3 ha^{-1}. The establishment of large (105 cm^3) nursery plants into spread residue produced the highest volume (212 m^3 ha^{-} - Figure 4.41) whilst the lowest volume (176 m^3 ha^{-1}) was recorded for the standard nursery plug planted into the same spread residues. Where *E. dunnii* seedlings were planted into spread residues, a large plug volume (≥105 cm^3) proved more responsive. Insecticide may have increased site volume due to the indirect effect of increasing survival, as blanking percentages were low. Insecticide applications were most likely effective against other insect types that do not necessarily kill the tree outright at planting but progressively set back growth.

5.4.4. EARLY TREATMENT RESPONSE - *E. DUNNII* MEDIUM PRODUCTIVITY SITE (E013) - 2 WEEKS POST PLANTING

Although the factor root plug volume (RPV) showed significant differences for height (m), Gld (mm) and biomass index (BI) ($p < 0.05$) 2 weeks after planting, this was expected as RPV differences already elicited responses in the nursery. Interactions for RPV x hardening were also significant ($p < 0.05$) for Gld (mm) and BA, but further interactions at 14 DAP were of no significance and further reporting focused on BA at 12 months for trial E013.

5.4.5. TREATMENT RESPONSE – *E. DUNNII* MEDIUM PRODUCTIVITY SITE AT 12 MONTHS (E013)

Two factors proved significant for basal area at 12 months, residue management (Table 4.21; Figure 4.27) and RPV. Burning was significantly more responsive where residues were retained and coefficient of variation values (22%) indicated a high degree of dispersion around the mean for residue treatments. Similar results were recorded for height and Dbh for these treatments and were not reported further.

Stomatal conductance at 12 months was significant for 1) Residue management, 2) Hardening and 3) Residue management x hardening x insect treatments. With a high CV value (30%) calculated, the dispersion around the mean reflected a spread indicative of the time taken to complete stomatal readings; however, the burn treatment still displayed the highest transpiration rate relative to other residue treatments and was most likely the impact of the availability of base cations and phosphorus (du Toit *et al*., 2008). With previous measures for growth, basal area and crown diameter all showing favourable responses to burning, the high stomatal conductance rate could not be interpreted as an indication of stress but rather active biomass accumulation in a vigorous performing timber stand, with soil moisture and nutrients non-limiting (Figure 4.28). The only treatment significant for chlorophyll conductance (CCI) at 12 months was nursery stock conditioned through water regulation but not to the detriment of plant vigour. The role of the chlorophyll content index in these experiments remained fairly unresponsive in terms of measured response and appeared suited to application in a more controlled environment.

5.4.6. TREATMENT RESPONSE – *E. DUNNII* MEDIUM PRODUCTIVITY SITE (E013) AT FINAL ROTATION

Two treatments, 1) RPV and 2) Residue management x RPV x hardening were significant at full rotation (99 months) for height (Table 4.26). The tallest mean height recorded (20.4 m) was for a large plug volume (105 cm^3) (supporting findings by Kiiskila, 1999; McCubbin and Smith, 1991), hardened in the nursery and planted into spread residue (Figure 4.42). The lowest mean height was recorded for a standard plug (60 cm^3), not hardened in the nursery, and planted into mulch (mean height = 18.5 m) (Figure 4.42). There were no significant mean Dbh differences measured at 99 months for any treatments and the role of plug volume, insecticide application and residue management became less distinct from mid-rotation (48 months).

The combination (Figure 4.43) of a burn treatment (97% survival) produced the highest stocking with the large plug = 1609 Spha and the standard plug = 1620 Spha. Residue management played a dominant role with the lowest stocking for spread residue combined with a large plug = 1493 Spha and spread residue x standard plug = 1377 Spha. A combination of burning and nursery hardening produced the highest stocking (1620 Spha - Figure 4.44) whereas the lowest stocking was recorded for seedlings that were not hardened and planted into spread residues (1377 Spha).

Basal area was not significant for treatments at 99 months whilst only RPV x hardening showed any significance for final volume, albeit at the 10% level. The best volume was produced by a large plug, not hardened in the nursery (188 m^3 ha^{-1}), with the worst performing (167 m^3 ha^{-1}) for an unhardened, standard nursery plug (Figure 4.45). Gomes *et al.* (2002) note that a well-stocked high yielding stand is very dependent on plant quality and must be able to resist adverse field condition and several cited authors (Guarnaschelli *et al.,* 2003; Thomas, 2009; Roland and Little, 2005) all refer to the importance of hardening nursery stock prior to establishment to ensure improved stocking. Gonçalves *et al*. (2008) and Stape *et al*. (2002) all report that under water and nutritional stress, residues retained on certain sites can increase nutrient availability.

5.4.7. EARLY TREATMENT RESPONSE - *E. GXN* MEDIUM PRODUCTIVITY SITE (F026) - 2 WEEKS POST PLANTING

Height gains measured 2 weeks after planting showed significant differences for the main factor, insecticide application and the interaction of RPV x hardening (Table; 4.19; Figure 4.21). This significance only manifested for height and not stocking which remained high (> 95%) at this measurement interval. Clonal responses to plug volume and hardening in the nursery were not as significant as for *E. dunnii* seedling trials at 14 DAP and was ascribed to a rudimentary clonal root system lacking in root volume that required more time after planting to respond to silviculture treatments. Gonçalves *et al*. (2008) and Souza (2002) report that *Eucalyptus* (including *E. gxn*) propagated from macro-cuttings have a root system, or a root architecture, comprising a non-pivoting root with several thick secondary roots that lack the ability to penetrate harder soils as pivoting roots, typical of what seedlings are able to do. Height measured two weeks after planting indicated that the interaction of RPV x hardening was significant; however, in retrospect this was simply too early to examine any treatment responses and was more a reflection of the quality of the nursery stock.

5.4.8. TREATMENT RESPONSE – *E. GXN* MEDIUM PRODUCTIVITY SITE (F026) AT 12 MONTHS

Height measured at 12 months (Table 4.21; Figure 4.29) for the medium productivity site (F026) showed significant differences for three separate factors, 1) Residue management (Figure 4.29) 2) RPV and 3) Hardening treatment. The nursery hardening protocol once again showed that water regulation in the nursery to not always be fully beneficial resulting in shorter plants across all plug volume treatments. A very fine balance exists between inducing some form of preconditioning in the nursery to deal with lowered soil moisture availability after planting and fine roots dying in the plug due to prolonged water deprivation. Thomas (2009) suggests that a method of drought hardening seedlings is to reduce irrigation, or induce a partial drought stress programme to pre-condition seedlings to the prevailing dry conditions they may experience shortly after planting. Residue management showed significant differences at 12 months with the same responses recorded in *E. dunnii* trials, with burning the best early performing residue treatment for height gain.

Dbh measured at 12 months showed significant differences for 1) Residue management, 2) RPV 3) Hardening, and 4) Hardening x insecticide (Table 4.21). Burning benefited Dbh gain similarly to height at 12 months, whilst Dbh was also significantly different for RPV. The benefits of nursery hardening on Dbh proved to be once again less beneficial. Zwolinski and Bayley (2001) state that for a particular container size, survival and growth is poorer in larger root bound seedlings than smaller optimum sized plants and authors tend to disagree on the relative advantages and disadvantages accruing to RPV and nursery hardening. The application of an insecticide was not significantly better than untreated plots with no bearing on Dbh, but definitely did benefit survival. The benefits of insecticide applications were measurable to canopy closure and maximum LAI; where after intraspecific competition for site resources became more important. Hakamada *et al*., (2020) state that an increment in light capture resulting from increased LAI can partially explain greater increases in stand biomass and is associated with higher transpiration rates that correlate to higher stomatal areas on both adaxial and abaxial surfaces. Results from trial F026 only indicated that certain silviculture applications were no longer significantly beneficial after canopy closure, as also documented by Crous *et al*. (2019). Du Toit (2008) states that increasingly, site-specific and operation specific silvicultural treatments are needed to optimally manage the supply of growth resources.

Survival at 12 months (Figure 4.30) showed significant factor effects for 1) Residue management 2) RPV and 3) RPV x hardening x insecticide; not the same combinations that impacted Dbh and height growth. A large plug, hardened in the nursery and treated with

insecticide produced the highest mean stocking level (1528 Spha) and would be a viable operational recommendation. Results indicated that survival showed a gradual decrease across three of the four trial sites (Figure 4.5) with mortality at trial F026 (*E. gxn*), decreasing to 1439 Spha by 12 months. Reasons for such mortality could not be attributed to abiotic or biotic stressors as plant quality and silviculture inputs were equal to experiment D01b. Survival declined during the final year of rotation, probably as severe intraspecific competition set in and possibly explainable in terms of the effects of the size-density relationship (Curtis, 2012). Tree stands that approach a high relative density near rotation end will be vulnerable, especially when combined with shallow root systems on wind-exposed sites.

Basal area at 12 months showed significance for 1) Residue management (Figure 4.31) 2) RPV 3) Hardening and 4) RPV x hardening x insecticide (Figure 4.32). Burning produced a significantly higher basal area than mulch and spread residues, a response likely driven by the early bioavailability of nutrients released through combustion. The large root plug also contributed to a higher basal area than the standard plug (large plug = 2.2 m^2 ha^{-1}; standard plug = 1.9 m^2 ha^{-1}) and hardening proved highly significant, with plants hardened through water deprivation/regulation performing poorest. Basal area for the RPV x hardening x insecticide interaction was primarily driven by the large plug consistently outperforming the standard plug, whilst significant benefits accrued where nursery plants were not subject to water regulation prior to planting. In summary, a large well-conditioned nursery plant outperformed the hardened counterpart and always outperformed the standard plug at 12 months (Figure 4.32).

Crown diameter at 12 months on burn treatments appeared to have benefitted from increased height and Dbh, whilst spread residue site was 42 % lower. Stomatal conductance at 12 months illustrated that a larger plug, not hardened in the nursery and planted with an insecticide drench produced the highest stomatal score, whereas the exact same treatment combinations applied to a standard 60 cm^3 plug produced the lowest stomatal conductance (Figure 4.33).

5.4.9. TREATMENT RESPONSE – *E. GXN* MEDIUM PRODUCTIVITY SITE (F026) AT FINAL ROTATION

The highest mean Dbh (14.8 cm) recorded at full rotation was a standard nursery plug not exposed to nursery hardening and planted with an insecticide drench. The lowest mean Dbh (13.9 cm) was recorded for a large plug not nursery hardened and planted with

insecticide (Figure 4.46). The larger plug recording a lower Dbh, with all other silviculture inputs equal at full rotation, indicated more of a site effect and a gradual dilution of individual silviculture interventions, with the onset of intraspecific competition. Plug volume and insecticide application were generally of greater importance than hardening; however, there was little treatment variation around mean Dbh at rotation end. The coefficient of variation for Dbh indicated lowered dispersions around the mean for burn treatments, as opposed to retained residues and was thus inferred that the initial uneven thickness of mulch created a barrier to early water infiltration or impaired pit quality that negatively impacted on early diameter gain.

Trial F026 sustained windstorm damage at 18 months that affected survival at 84 months with a minor degree of toppling post the windstorm. It was difficult to attribute the later toppling to wind damage, treatment effects or a delayed effect of wind on certain treatments. The large plug showed better stocking (1316 Spha) than standard plug (1196 Spha), whilst nursery hardening appeared to negatively impact on stocking, with treatments not hardened performing worse than hardened plants. It must be considered whether nursery hardening did not have a deleterious effect on root biomass or alternatively caused fine root dieback due to excessive water deprivation. The combination of a large plug, primed in the nursery with insecticide applied at planting interacted favourably to produce the best overall survival at full rotation (1389 Spha - Figure 4.47). The worst performer (1096 Spha) for a standard plug (Figure 4.47), hardened in the nursery with insecticide applied at planting would tend to back the former optimum combination of treatments. On several occasions, the standard plug showed poorer field results if hardened in the nursery indicating the possibility of the onset of the desiccation of fine root hairs in the plug and a loss of active root growth prior to planting. This impact was also detected where nursery hardening decreased BA means (20.4 m^2 ha^{-1}), whilst planting stock that was subject to a daily nursery watering regime (watered to field capacity) was higher at 21.7 m^2 ha^{-1}.

5.4.10. EARLY TREATMENT RESPONSE - *E. GXN* HIGH PRODUCTIVITY SITE (D01B) - 2 WEEKS POST PLANTING

Gld measured two weeks after planting revealed the factors plug volume and insecticide to be significant with height responsive at an earlier stage. Experiment D01b again verified that measurements 2 weeks after planting were premature and should be delayed until 3 months. The primary focus at 14 days after planting was to ensure blanking was completed early for greater crop uniformity. There are also added benefits accruing from follow up watering within these first two weeks after establishment and additional insecticide drench.

5.4.11. TREATMENT RESPONSE – *E. GXN* HIGH PRODUCTIVITY SITE (D01B) AT 12 MONTHS

Height at 12 months, showed significant differences (Table 4.21) for only one factor, nursery hardening and highlighted that water deprivation in the nursery aimed at improving initial survival did have a negative impact on height growth, most likely due to a watering regime resulting in nursery plugs drying out too much. Survival did not significantly gain from the nursery hardening programme. Dbh measures (Table 4.21) in this trial showed that residue management treatments responded differently to the equivalent *E. dunnii* seedling trials. For the first time in four trials, the burning treatment did not rank first for residue management but the three treatment differences were very low.

Crown diameter at 12 months revealed that burning combined with no nursery hardening produced the best diameter (0.9 m) whilst the poorest performer was burning combined with a nursery hardened treatment (dia = 0.6 m) (Figure 4.35). Stomatal conductance and chlorophyll content index (CCI) at 12 months showed no significant differences and reinforced earlier findings that such field measurements in the field close to canopy closure were of doubtful value and may be better assessed through the measurement of leaf area index. Stomatal conductance and CCI appear better suited to pot type trials with environmental conditions more strictly controlled.

5.4.12. TREATMENT RESPONSE – *E. GXN* HIGH PRODUCTIVITY SITE (D01B) AT FINAL ROTATION

The tallest mean height (22.7 m) was recorded for a standard plug x insecticide treatment, with the lowest mean = 21.9 m (Figure 4.48). The best mean Dbh was significant (Figure 4.49) for a standard plug that had been primed in the nursery through irrigation regulation (Dbh = 14.7 cm). A burn treatment planted to a standard 60 cm^3 plug produced the lowest spread of Dbh measures (CV = 18%), whereas the worst mean (Dbh_CV = 28%), occurred where a standard plug was planted into spread residues (Figure 4.50). These findings supported the assumption that unevenly spread residues can have a negative impact on the uniformity of a stand, most probably due to the disruption of airflow through early plantings. There were no strongly significant differences in mean survival with the best only weakly significant for hardened nursery plants established on a burnt site (1586 Spha) and the lowest (1458 Spha) where unhardened nursery stock was planted into mulch or spread residues.

The highest mean BA (27.9 m^2 ha^{-1}) was recorded for a standard plug hardened in the nursery, with the lowest (24.1 m^2 ha^{-1}) for an unhardened plug with the same plug dimensions (Figure 4.51). This finding conflicts with the previous *E. gxn* experiment site (Trial F026) where hardening decreased BA means (20.4 m^2 ha^{-1}), whereas planting stock not subject to drought hardening showed a greater BA (21.7 m^2 ha^{-1}).

The highest mean volume (243 m^3 ha^{-1}) was recorded for a standard plug hardened in the nursery, with the lowest volume (185 m^3 ha^{-1}) for an unhardened plug with the same plug dimensions (Figure 4.52). The synergistic effect of combining plug volume with hardening in the nursery produced a major volume difference, quite contrary to the hypothesis whereby a large plug volume should outgrow its smaller counterpart. In summary, a combination of plug volume x hardening x insecticide remained an excellent overall recommendation, even more important than the residue management responses.

5.5. EXPLAINING TRIAL DIFFERENCES IN TERMS OF ABSOLUTE AND RELATIVE DIFFERENCES

Relative growth rate (RGR) has grown in importance in differing fields of science and proven invaluable in plant growth analysis, especially in assessing growth performance and growth efficiency, and is simpler to model than absolute growth rates (Pommerening *et al.,* 2016). RGR offers a standardised measure of the productive capacity of a tree and allows for comparison that differ in initial size, age and environmental conditions (Larocque *et al.,* 1993). RGR is therefore a function of time and defined as the increase in size relative to the growth characteristic (Pommerening *et al.,* 2016). The absolute growth rate (AGR) depends on the current state of the plant size measure and is not very helpful when comparing plants of different size (Causton *et al*., 1981). In such a situation, RGR (relative increment in forestry terms) is preferred to AGR. Wenk *et al*., (1990) state that relative growth is an expression of growth energy or growth vigour whilst Causton (1977) adds that relative growth rate is the measure of the efficiency of plant material to produce new biomass and has important physiological characteristics.

The periodic or mean absolute growth rate is the difference in the value of a particular morphological characteristic at different times. When absolute growth rate (AGR) is positive the plant size characteristic is growing (Pommerening *et al.,* 2016). Fisher (1921) defined mean RGR as the amount of change per unit area of material per unit area of time. In recent times, RGR has reflected the systematic variation in physiology, allocation and leaf construction (Houghton *et al.,* 2013). Larocque and Marshall (1993), in a study of the

relationship between RGR and competition in *P. resinosa*, highlighted that RGR decreased with increasing tree size before the onset of competition. Under competitive stress, RGR increased with tree size and concluded that small trees are often more efficient at producing greater biomass before the onset of competition. However, competition reduced the efficiency of small trees relative to larger trees. Pommerening *et al.* (2016) state that RGR is a simpler measure with fewer parameters than AGR and that modelling RGR growth has more advantages over absolute growth than just removing the influence of size.

5.5.1. HIGH PRODUCTIVITY SITE (D010): ABSOLUTE AND RELATIVE DIFFERENCES IN MEAN BASAL AREA – *E. DUNNII*

Burning produced the largest mean BA through to full rotation (Figure 4.53). Mulch and spread treatments responded similarly but mulching showing the smallest basal area gains from 5 years onwards, confirming that benefits of mulching of fertile sites with moderate water deficits to be of little economic value (Figure 4.53a; Figure 4.55). Absolute BA differences generally favoured no hardening (Figure 4.54a; Figure 4.55), whilst insecticide showed low absolute differences initially for 2 years before increasing to 1.05 m^2 ha^{-1} by full rotation (Figure 4.55).

The large plug volume outperformed the standard plug to full rotation (Figure 4.55). In terms of absolute differences, plug volume continued to have an impact but the relative difference remained constant. No nursery hardening of planting stock revealed higher mean basal area, except from 1 to 2 years, but thereafter, hardening through water deprivation in the nursery showed a consistently lower mean BA, possibly due to dieback of root volume prior to planting (Figure 4.55). Although hardening in the nursery does have recorded early benefits, excessive hardening can affect BA, although it is unlikely to have done so as late as 5 years and could have been possibly due to the partitioning between above and below ground growth, with hardening generally favouring the below ground components.

5.5.1.1. RELATIVE DIFFERENCES: BASAL AREA – SITE D010

Relative mean BA differences showed minor gains to 2 years in favour of burning over retained residues (Figure 4.56 – black dotted line); however, the long-term relative differences were negligible at full rotation. RPV (Figure 4.56 – blue line) showed strong early relative gains up to 1 year but diminished to zero at full rotation. There would be little value in significant silviculture input costs for such low BA returns; however, this scenario may be different on drier more marginal sites. Nursery hardening and insecticide

applications (Figure 4.56) revealed relative differences in the first three months (silviculture input benefits), but thereafter no real BA gains accrued over the standard treatment with the onset of intraspecific competition, driven by water deficit responses, and to a lesser degree, soil nutrient capital. The impacts of relative density should not be underestimated, but would form part of the intraspecific competition component so not strictly a silvicultural response, other than indicating that tree spacing for a specific rotation may require a review. In summary relative differences between treatments showed little impact on mean BA indicating early silviculture gains diminished with time.

5.5.2. MEDIUM PRODUCTIVITY SITE (E013): ABSOLUTE DIFFERENCES IN MEAN BASAL AREA – *E. DUNNII*

Burning recorded the largest mean BA, a response attributed to freely available nutrients through to full rotation at 2985 DAP (Figure 4.57 a: Figure 4.59 – black dotted and dash lines). RPV continued to impose a positive impact but absolute differences remained constant over time (Figure 4.59 - blue dash line). In summary, residue treatments and RPV showed an initial divergence from 1 year after planting, but this diminished indicating these treatments were having little impact over time. The absolute differences in BA between no hardening and hardening treatments were minor (Figure 4.59 – green dash line) whilst the insecticide application, from 1 – 8 years, revealed a larger mean BA for both *E. dunnii* trials. This was likely due to higher survival as well as the removal of losses inflicted by biotic agents that do not necessarily kill the tree but set back growth performance.

5.5.2.1. RELATIVE DIFFERENCES: BASAL AREA – SITE E013

Relative differences in mean BA showed good gains up to 1 year in favour of burning over residues (Figure 4.60 – black dotted and dash lines), with treatment comparisons following the same graphical trends. Long-term relative differences for residue treatments were negligible for mean BA by end of rotation. The value of relative differences lies in the ability to encapsulate absolute gains or losses at a specific time, relative to a standard treatment. Where treatment differences do not diverge, the relative differences will disappear with time and a decision to invest in a specific treatment(s) unwarranted.

Plug volume recorded initial relative BA gains up to 3 years, diminishing to zero at full rotation. Gains were consistent with the high productivity site that showed a peak relative gain at 1 year. Both trials declined to zero BA increase at full rotation. Hardening and insecticide applications showed relative differences in the first three months, but thereafter

no BA increases over standard treatments (Figure 4.60 – blue dash line). In summary, relative differences between silviculture treatments all showed positive increases to 3 years, but declined thereafter indicating that early gains were of lesser impact if not fully expressed by 3 years. The onset of intraspecific competition driven by the complexities of fluctuating water deficits and site nutrient availability would become more important as cited by Du Toit and Dovey (2005); Du Toit (2008); Du Toit *et al*. (2010); Crous *et al*. (2019).

5.5.3. HIGH PRODUCTIVITY SITE (D01B): ABSOLUTE AND RELATIVE DIFFERENCES IN BASAL AREA – *E. GXN*

Basal area differences between burn and spread (slash) treatments initially favoured burning, reaching a peak 2 years after planting in a very similar fashion to the *E. dunnii* trials (Figure 4.63 – Black dotted and Black dash lines). By 3.5 years, absolute differences between burn and spread residues ceased to exist (Figure 4.63 – dash line) and results would reverse with retained residues becoming more dominant. This was quite the converse to the *E. dunnii* trials where burning would drive greater BA. Absolute differences between burning and mulching always favour mulching (Figure 4.63 – Black dotted line). This was again the reverse of results emanating from *E. dunnii* trials where burning showed greater gains at full rotation.

Although the large plug volume recorded initially higher BA increases (Figure 4.63 – Blue dash line), this would decline at 18 months and the standard plug would then produce greater gains (BA gain = 0.85 m^2 ha^{-1}) by rotation end. In summary, a large plug (105 cm^3) performed best for *E. dunnii* whereas the standard plug (60 cm^3) performed better in the *E. gxn* clonal trials. Initial differences favoured not applying nursery hardening up to 3.5 years, but thereafter, the nursery hardened treatment surpassed unhardened treatment by 1.2 m^2 ha^{-1} at full rotation (Figure 4.63 – Green dotted line). Insecticide treatment displayed a similar gain over the no treatment option and responding in a similar fashion to *E. dunnii* trials at 8 years (Figure 4.63 – Red dotted line).

5.5.3.1. RELATIVE DIFFERENCES: BASAL AREA – *E. GXN* – SITE D01B

Relative BA differences between burning and spread showed initial small gains in favour of burning (max. = 0.180 m^2 ha^{-1}) but declined to zero by full rotation (Figure 4.64 – Black dash line). Root plug volume showed minor early gains to 18 months in favour of the standard plug but declined to zero thereafter (Figure 4.64 – Blue dash line). All trials showed declining BA gains for differences in root plug volumes by full rotation after experiencing peak

differences at 1 to 3 years. Relative BA gains through not applying nursery hardening (Figure 4.64 – Green dash line) were also significant up to 3 years, but thereafter negligible, as were insecticide treatments (Figure 4.64 – Red dash line). In summary, relative differences between silviculture treatments showed minor early gains up to 3 years, but declined to zero by full rotation. Silviculture treatments ranged from highly responsive at planting to a threshold at 3 years. Thereafter, site characteristics dominated by water deficit and soil fertility would become more important as interspecific competition increased, as supported by Ryan *et al.* (1997); Gonçalves *et al*. (2013); Crous *et al*. (2019). Du Toit (2008) reports that very few, if any, silvicultural tending operations are applied from canopy closure until clear felling since vegetation and fertilisation management practices after canopy closure have proven not cost effective under water limiting conditions. A lack of process-based understanding of tree growth in response to resource availability constrains efforts to increase productivity in a sustainable way.

5.5.4. MEDIUM PRODUCTIVITY SITE (F026): ABSOLUTE AND RELATIVE DIFFERENCES MEAN BASAL AREA

Basal area differences revealed that 6 months after planting treatment divergence grew in earnest. Initial differences between burning and mulch (Figure, 4.65; Figure 4.67 – Black dotted line) favoured burning up to 4 years but declined rapidly and by full rotation only differed by 0.13 $m^2 ha^{-1}$. This was the reverse of results from *E. dunnii* trials where absolute differences between burning and mulching favoured burning at 0.8 $m^2 ha^{-1}$.

At 6 months after planting the large plug produced a greater BA through to full rotation (Figure 4.67 – Blue dotted line). On the high productivity site (*E. gxn*) with lower mean water deficits (trial D01b), the standard plug produced greater BA gain, whereas on the *E. dunnii* trials with higher mean water deficits, the large plug showed higher increases. In summary, a large plug cavity volume (105 cm^3) performed best for both *E. dunnii* trials and a single *E. gxn* trial. The reasons for the different performance at this experiment (trial F026) is attributed to toppling and windstorm damage at 18 months and unlikely as a result of treatment responses.

Absolute differences favoured no nursery hardening (Figure 4.67 - Green dash line) with increasing BA gains to full rotation. In the comparative *E. gxn* experiment (trial D01b), the hardened treatment produced a higher mean BA at rotation end. The results for clonal trials, although conflicting for nursery hardening and plug volume, emphasized that single factor responses do not drive results but are only contributory or additive. Final yield is the

cumulative effect of multiple silviculture drivers combined with environmental conditions in time. Insecticide treatment displayed increasing differences with time, reaching 1.0 m^2 ha^{-1} by 7 years (Figure 4.67 – Red dotted line). A similar response was observed for *E. dunnii* and gains through insecticide treatment the most definitive across all trials.

5.5.4.1. RELATIVE DIFFERENCES: BASAL AREA – SITE F026

Although the medium productivity site (F026) produced the lowest grand mean volume, it was the most responsive in terms of relative differences for treatments. Whether the lowest volume could lead to the highest expression in relative differences appears counterintuitive and lower stocking levels due to windstorm damage may have influenced this 18 months after planting.

The relative difference between burning and mulching (Figure 4.68 – Black dotted line) were of lesser consequence and declined to zero by full rotation. In summary, the cost of mulching residues at approximately R 9,000 ha^{-1} on such fertile sites was not financially viable and not a sound silvicultural or economic consideration without other driving factors such as soil erosion and fire protection considered. Plug volume (Figure 4.68 – Blue dash line) showed an initial spike favouring the large plug but declined to zero by end of the trial. In all four trials, there was an initial response to root plug volume to 3 years but this disappeared by full rotation, whilst insecticide treatment as a soil drench (Figure 4.68 – Red dash line) did show minor relative mean BA gains up to rotation. In summary, relative differences between treatments all showed promising early gains from 3 months, but declined to a static level at 3 years, remaining constant until full rotation.

5.5.5. WHAT COMBINED TRIAL RESULTS ILLUSTRATED

A number of main effects and interactions were strongly significant (5% level) at final rotation for the combined experiments for the variables height, Dbh, stocking, BA and MAI. Main effects included: 1) Site, 2) Residue management and 3) Insecticide (Table 4.31). Highly significant interactions included: 1) Site x RPV, 2) Residue management x RPV, 3) Residue management x hardening, 4) RPV x hardening, 5) Site x RPV X hardening, 6) Residue management x RPV x hardening, 7) RPV x hardening x insecticide (Table 4.31).

5.5.5.1. SURVIVAL

Survival tended to favour nursery stock raised in a larger cavity plug combined with no nursery hardening, followed by two insecticide drenches at planting. Planting on burned

sites produced higher stocking levels than into retained residues but the three combined treatments were of greater significance than residue alone. Although Thomas (2009) suggests that a method of drought hardening seedlings is to reduce irrigation, or in duce a partial drought stress programme to pre-condition seedlings, the challenge remains as how to pre-conditioning nursery stock but not to the point of partial root damage that is invisible to the eye, but manifests in the presence of hydraulic and thermic stress.

5.5.5.2. DBH AND HEIGHT

Only one interaction, RPV X hardening, was strongly significant for Dbh at 99 months across all four experiments, with no conflict for interactions of significance with stocking noted (Figure 4.72). The best performing Dbh at 99 months was for the large plug volume not hardened in the nursery. Height at 99 months was significant for residue management x RPV x hardening as further reported for MAI (Figures 4.73 and 4.76).

5.5.5.3. BASAL AREA AND MEAN ANNUAL INCREMENT

For BA, the three way interaction of factors 1) Site x RPV x hardening and 2) Residue management x RPV x hardening were strongly significant ($p < 0.05$) at 48 months but only weakly ($p < 0.10$) significant at full rotation. In terms of MAI, the best performing treatments across sites were attributed to the presence of a large plug planted on a spread treatment (MAI = 24.8 m^3 ha^{-1}) (Figure 4.75). The inclusion of insecticide improved stocking and indicated a positive survival response (Figure 4.76). As more treatments, i.e. insecticide were added to increasingly complex interactions, the more statistical significance grew in favour of stocking but decreased for MAI ($p = 0.345$); most likely indicative of increasing intraspecific competition for water and nutrients on the site as full rotation age approached (Gonçalves *et al*., 2013). The impact of relative density (Curtis, 2012) must also be strongly considered at this point and it is likely that the optimum rotation age was clearly reaching a peak.

5.5.5.4. COMBINED TRIALS – ACCOUNTING FOR BASAL AREA VARIANCE

At full rotation, BA differences were only explainable in terms of site, explaining 40% of differences whilst main silviculture factors accounted for only 4%. The interaction of RPV x hardening remained significant to full rotation, although only able to account for 9% of BA differences. In summary, BA differences were mostly explainable by site, and to a lesser measure, nursery practices, but silviculture treatments such as insecticide applications and

residue management were not significantly different by rotation end. Du Toit (2008) refers to large increases in productivity from early intensive silvicultural management operations that attempt to optimise the supply of growth resources to the newly established crop. These include residue management and site preparation techniques, watering at planting, fertilisation at establishment, followed by intensive weed control up to canopy closure. Little and Rolando (2002) add that very few silviculture tending operations are continued from canopy closure through to clearfell as they are not cost effective under water limiting conditions. Binkley *et al*. (2004); Du Toit and Dovey (2005) note that an understanding of the response mechanisms of a stand to changes in resource availability brought about through silvicultural practices will facilitate such an extrapolation.

Du Toit (2008) makes reference to the allocation of transient components such as fine root production and litter fall to carbon distribution amongst biomass components of eucalypts. At the macro silviculture scale there would appear to be a transient period when certain silviculture treatments play a more important role, whilst others lose momentum between canopy closure and the onset of greater intraspecific competition. A series of staggered cut-off points when main silviculture treatments gradually cease showing significance and site dominance arises. The process is more of an evolving gradation from the absolute dominance of main silviculture effects, from establishment to canopy closure (peak LAI), to the emerging dominance of site-specific factors, such as soil moisture and soil fertility, that ultimately drive intraspecific competition through to full rotation.

5.5.5.5. THE IMPACTS OF WATER DEFICIT ON BASAL AREA

Water deficits over the full rotation of the four experiments were plotted (Figure 4.77) with basal area (current basal increment and cumulative) growth trajectories for the same periods (Figure 4.78). Water deficits to full rotation were comparable across the two *E. dunnii* experiments, with BA commensurately low prior to canopy closure. In the *E. gxn experiments,* planted in 2012, WD levels in the first year were much higher (97 mm y^{-1}) and BA measures remained low (Figure 4.78) as clonal plantings directed resources to the below ground biomass to offset higher water deficits. This change in deployment of carbohydrates would definitely impact on above ground biomass. It is debateable as to whether a tree crop planted during a water deficit situation is ever able to fully realise the total volume potential of the site over the rest of the rotation, even when water deficits decrease to minimal in following years.

By the end of the first year, water deficits had increased nearly 10 fold from initial values for the *E. dunnii* sites, yet still recorded acceptable basal area ranges. At 2 years after planting, WD for the *E. dunnii* sites varied very slightly (79 mm) and were comparable in terms of cumulative BA, although the rate of current BA increment differed. Water deficits for the *E. gxn* experiments 2 years after planting were higher (111 – 128 mm y^{-1}), yet both sites produced good current basal area. The negative impacts of a high WD on early-established plantings must play an integral role in their performance in later years and the ability to translate this into deposition of wood fibre. The *E. gxn* trials experienced much higher water deficits in their first year of planting than the *E. dunnii* counterparts and hence their BA performances were surprisingly favourable under the drier circumstances, although Campion *et al*. (2006); Stape *et al*. (2008) state that a strong positive relationship exists between water supply and wood production for eucalypts.

BA increment tends to increase immediately after canopy closure as leaf area is at maximum and the partitioning of carbohydrates to foliage is lowered after reaching peak LAI, in favour of partitioning to stem wood. One would thus expect a peak BA increment between 2 to 4 years, depending on site indices (Du Toit, 2008; Coetzee, 1999) and may lag behind water deficit curves slightly. This was apparent in the trial series at 4 years (mid-rotation) where WD for *E. dunnii* experiments were relatively high (157 – 168 mm y^{-1}) with current BA across sites producing 6.0 – 8.0 m^2 ha^{-1} yr^{-1} in the same year. At 4 years after planting, current BA for *E. gxn* experiments had decreased (4.4 m^2 ha^{-1}) for the same water deficit range. Although by mid rotation (4 years) both genotypes performed evenly in terms of cumulative BA, the *E. gxn* trials sites produced lower current BA, nearly 20% less under the same WD conditions. This could point to the onset of the impacts of intraspecific competition with current BA more negatively affected by higher water deficit conditions.

At 6 years (Figure 4.78) after planting, all sites experienced fairly low WD conditions, but also decreasing current BA and the impacts of increasing relative densities were likely to be of greater importance as final rotation ages grew closer. For both genotypes, current basal areas peaked between 3 to 4 years. Data indicated that under similar water deficit ranges (Figure 4.77), the clone produced basal areas equal or even slightly lower than the seedling (Figure 4.78). It was quite evident that the clone not only requires wetter site conditions, but that these conditions should be equally distributed across the full rotation, with any high water deficits more likely to negatively impact on basal area than experienced by *E. dunnii*. The ability of *E. dunnii* to better cope with fluctuating water deficits and still record consistently high basal areas points to the drought resilience of the species and possibly greater water use efficiency (Figure 4.79). The role of such species in terms of their

ability to withstand thermic, hydric and biotic stress will grow increasingly important with the onset of climate change. Hamer *et al.* (2016) report that eucalypt species from drier zones (ex. *E. dunnii*) have a higher root to leaf area ratio and this process of investing more carbon in the roots could be a strategy to sustain growth during drier periods.

5.5.5.6. ABSOLUTE AND RELATIVE DIFFERENCES FOR COMBINED TRIALS

Absolute BA differences between residue management treatments were minor at full rotation (Figure 4.82 – Black dash line), whilst root plug volume consistently favoured the larger plug (Figure 4.82 – Orange dash line). Small increases through to full rotation were noted where no nursery hardening was applied (Figure 4.82 – Green dash line) and results indicated that response to hardening were genotypically responsive but surprisingly of little consequence at the grouped level. The insecticide factor (insecticide vs. no insecticide application) (Figure 4.82 – Blue dash line) showed no differences in mean BA up to 3 years, but thereafter insecticide treated plots revealed increasingly positive BA gains to full rotation (Figure 4.82 – Blue dash line).

Relative differences in mean BA between burning and mulch showed differences to 3 years but dissipated thereafter (Figure 4.83 – Black dash line), whilst RPV revealed an early BA increase at 3 months (Figure 4.83 – Orange dash line) but declined to zero by end of the trial. Small relative increases accrued by not applying nursery hardening (Figure 4.83 – Grey dash line) up to 1 year, but thereafter were negligible for the duration of the trial. In summary, relative differences between silviculture treatments revealed promising early increases from 3 months after planting but all declined to zero at 4 years and remained so through to full rotation. The impact of site conditions, soil moisture and site fertility, became increasingly stronger at the transition period of 3.5 to 4 years as intraspecific competition grew in intensity.

5.6. SUMMARISING MAIN AND INTERACTIVE TRIAL RESULTS

Stape *et al*. (2004) states that the productivity of forest plantation is limited by water availability as a lack of nutrients can be mitigated through fertilisation. Prior to canopy closure, trees are more responsive to cultivation, fertilisers and weed control (Gonçalves and Mello 2004; Du Toit, 2008) and silviculture treatments contribute slightly more to productivity improvement than tree improvement or species choice for main factors across differing site productivities and species (Pallet and Boreham, 2009). After canopy closure, intraspecific competition for resources increases and is more pronounced in resource-

limited environments (Figure 4.80; Figure 4.81) (Du Toit, 2008; Binkley *et al*., 2004). According to Ryan *et al.* (1997), the age of peak leaf area index (LAI) coincides with the highest rate of biomass production and requirement for evapotranspiration (Gonçalves *et al*., 2013). Du Toit *et al*. (2010) showed that the effects, interactions and response mechanisms of intensive silvicultural practices were all additive when applied simultaneously, emphasizing the need to optimise each practice.

With cited literature considered, and based on experiment results from this study, it is possible to state with a fair degree of certainty that silviculture inputs such as plug volume, residue management, nursery hardening and insecticide application, all applied simultaneously at establishment are most responsive (in terms of significance difference) from planting to approximately 3.5 years (Figure 4.82). Thereafter, their individual and combined effects became increasingly difficult to explain through either main or interactive effects. Even the sum response of three to four interacting silviculture treatments could only explain less than 15% of variability after canopy closure, even where significant differences exist (Figure 4.82). However, a number of factors showed some consistency. For example, large nursery plants generally did not benefit from hardening in the nursery, whilst the smaller cavity volume did show a definite need for nursery hardening. Most of the main effects (factors) showed early responses (Figure 4.82); however, as trials progressed with time, treatment interactions became more important (Figure 4.83). The reporting of early positive gains from 1 – 3 years, albeit plug volume, residue management, insecticide application or hardening did not necessarily retain that rank as trials grew older. Hence, plug volume was significant at an early stage in the trial but lost its significance with time to form only part of an interaction. Factors that were important early in trial assessments disappeared with time.

Boreham and Pallet (2009) state that in many cases, the potential gains associated with main factors are not realised at the operational level as the individual components are poorly integrated and yield improvements are less than anticipated (Boreham and Pallet, 2009). For this study, measurements such as stocking and MAI showed different responses to certain treatments, but for explainable reasons. Stocking is highly responsive to early silviculture treatments but less so to site, unless there is a catastrophic collapse due to biotic or abiotic stress early in the rotation. Hence, stocking will generally be explainable in terms of early silviculture inputs, either through main or interactive effects, over the full rotation.

Growth measurements such as basal area and mean annual increment are initially reliant on effective silviculture inputs (Du Toit, 2008). Gonçalves and Mello (2004) add that there

has been significant improvements in silviculture practices, including seedling quality, site preparation, planting density, residue management, weed control and pest management, that all contribute to improved site water management and increased resilience to drought. Industrial eucalypt species often express comparative extravagant water use and rapid hydraulic failure under prolonged water deficits (Mitchell *et al*., 2013b). This is primarily because most eucalypts planted to industrial type plantations are native to high rainfall areas (Weston *et al.,* 1991; Madeira *et al*., 2002) and already grow within a very narrow range of tolerance to drought. This can be attributed to species evolution whereby shallow rooting species in water rich environments do not significantly alter the balance of biomass as a function of water availability and die quickly (Bloom, 1985), whilst deep rooting forest species (*E. dunnii*) develop great volumes of thicker roots that colonize moister soil. The key to survival is longer specific root length to resist water stress (Padilla *et al*., (2015) whilst shallow rooting species (*E. gxn*) concentrate fine root production in the top 40 cm of soil (Hoffmann and Kummerow, 1978).

The prevalence of more frequent, and prolonged dry periods, accompanied by higher mean annual temperatures (MAT), are driving higher soil water deficits resulting in greater plant mortality (Jentsch et al., 2007) or depressed stand volumes. This response is consistent with the resource partitioning theory where plants increase the ratio between water absorbing and transpiring surfaces (leaf area in this case) in response to a water deficit (Bloom, 1985) and may explain to a certain degree why tree growth becomes increasingly responsive to the effects of water deficits and nutrient capital in terms of the onset of intraspecific competition, from about mid-rotation (3.5 – 4 years) through to final rotation.

5.7. SIGNIFICANCE OF STUDY

This report set out to examine the interaction between site, harvest residue management and nursery stock quality on the survival, growth and uniformity of two temperate eucalypt genotypes across four sites of narrow soil and climate range in the Midlands of KwaZulu-Natal. Experiments were statistically sound and produced large data sets that can be further examined with reference to similar studies. The first part of the study reinforced the role of silviculture practices to canopy closure and thereafter, the increasingly important role of intraspecific competition. The first section of the study has been well researched in South Africa with a clear understanding of the importance of silviculture practices, including the selection of robust nursery stock, well prepared pits, planting with water and fertilisation.

The importance of canopy closure is generally underestimated and its overall role to the final stand yield is critical. It is a very important juncture whereby inputs of silviculture slowly start to fade in significance as the importance of site quality and competition come to the fore. There is a tendency to oversimplify canopy closure as a simple interval in the growth cycle whereby foliage and branches start to overlap, overlooking the fact that rapid root growth and hence below ground competition for resources has been ongoing. Instead of canopy closure, we should rather see this transition when leaf area index reaches a zenith and thereafter, the importance of intraspecific competition overrides all silviculture inputs. The importance of firstly water deficits, and secondly, site nutrition, now become paramount. Any silviculture inputs, other than pest control and pruning, are of little consequence thereafter in unthinned, short rotation stands.

In this study, the role of a number of important silviculture factors were positively reinforced. Our current nursery practices are not keeping abreast with the rigours of early silviculture demands and these must be reviewed in order to make re-establishment more robust and to better able withstand the vagaries of local conditions. The role and utilisation of a larger plug volume is fairly well defined in this study and in numerous other excellent cited literature; however, most nurseries still adopt a fairly simplistic and mechanistic approach of a one size fits all sites, when the importance of site specific silviculture is really starting to emerge with the onset of mechanised silviculture. Operationally, nurseries will need to consider the operational deployment of larger, more robust nursery stock. Of paramount importance is our approach to nursery hardening as several current practices may be causing greater harm to the root plug than good.

The conventional approach of regulating nursery irrigation may lead to the death of fine root growth in the plug if growth media is allowed to dry out excessively. A single poor watering schedule can result in the dieback of parts of a root system, already distorted by the unnatural shape and limitations of the nursery cavity. Once root hairs die, a whole or partial new network will have to recolonise the plug, which cannot be achieved within the time constraints of nursery production. This experiment showed that regulating nursery watering too harshly produced deleterious results (although plug size specific). A greater focus on hardening nursery stock through greater exposure to light and airflow by double spacing of plants in trays must be reviewed. Competition for light is generally overlooked in nurseries; however, it is critical if secondary bark deposition and suberisation of leaves are to be enhanced. Plants well-spaced apart in the nursery, at least one month prior to dispatch, have shown to be much hardier with a fully colonised root plug and the relocation of growth resources to root plug. The slow introduction of the paper pot systems must be investigated

as the advantages of various volume sizes available are better suited to a more site-specific silviculture approach and such plants are generally much more robust. In summary, nursery hardening processes must be reviewed with a focus rather on exposure to light and air movement, through double spacing, as opposed to attempting to regulate irrigation, often excessively, resulting in the mortality of portions of healthy root systems that remain substandard.

The role of insecticides in establishment are absolutely essential and the restrictions based on the application of a greater range of pyrethroid based insecticides with longer residual actions are unfortunate. Root pests tend to be of two categories, those that kill the plant crop out-right through physical destruction of the root system and the group responsible for damage that is less noticeable, but set back early survival, growth and uniformity without realisation as to the extent of the loss. In the view of this study, it is highly recommended that insecticides be applied as a soil drench at planting, followed by a reapplication within 10 days. Failure to do so can result in variable impacts on survival, growth and uniformity.

Residue management results from this study would initially appear to be in conflict with what is regarded as conventional wisdom but this would be a gross over simplification of the practicalities facing the forester. Driven by forest certification bodies and the ban on burning in parts of the world such as Brazil, prescribed burning of residues is often described as an obsolete and irresponsible practice by forestry companies to simply avoid implementing more environmentally friendly residue management alternatives due to costs. A significant portion of this study was focused on three distinct residue management techniques, burning, mulching and retention of spread. The initial hypothesis implied that the costs of mulching would be offset by the added benefits of moisture retention, increased nutrient availability from residue retention, avoidance of a carbon tax due to burning, lowered greenhouse gas emissions and increased volume. This was to prove inaccurate over the four experimental sites and mulching did not improve growth characteristics and was thus not superior to retaining slash nor burning. Although the environmental benefits of mulching are beyond dispute in preventing physical erosion through wind and rain, the costs per hectare are high and not practical on the broad scale in the Midlands of KZN or where terrain is steep and rocky. On the resilient soils of the Midlands (high clay and organic matter contents), differences between burning and retained residues at rotation end were not significant and the costs of mulching simply too high to advocate. The threats of fire through known arson incidents account for more than 70% of all fires in South Africa and the problem is growing in intensity. Although prescribed burning of residues should be strictly controlled, a total ban would be counter-productive in the South African context. It is imperative that

we recognise that South African ecosystems are fire adapted and although we must continue to learn from international exposure, we can simply not adopt all policies without reviewing the many local threats. The role of mulching; however, is fully advocated for the sandy, sensitive soils of coastal Zululand, with small nutrient pools and will likely highlight numerous benefits for such an environment.

The role of site classification has focused on identifying factors such as soil form, ameliorated soil depth, plant available water, depth limiting layers, soil fertility, mean annual precipitation and mean annual temperature. Most site classifications are just basic site descriptors that assist in the selection of the correct species and cannot be regarded as an 'intelligent' classification system. Fortunately, local scientists and academics have realised this shortcoming and comprehend the urgent need for a more robust site classification system. The one driving factor that must be included in any future classification system is the critical role of water deficits and fertility traits focused on available N and mineralisable P, as opposed to simple mean annual precipitation. This requires an understanding of hill-slope hydrology and true root access into the soil and underlying layers. Annual water deficits are far more informative in terms of the impacts of survival, growth and uniformity.

5.8. STUDY LIMITATIONS

In summary, the study achieved most of its objectives and in many cases contributed a clearer understanding of the additive effect of silviculture inputs and the transition to intraspecific competition, so long advocated by local scientists. For this author, this transition is now much clearer and the concept of site specific silviculture regimes just that more important going into the future. However, the hindsight garnered from experiments does mean that trial site selection would be different if attempted again. As opposed to selecting four very similar sites and two separate genotypes, it would be more focussed to choose four sites of greater variability in terms of soil form, soil depth, and MAP range, all planted to a single commercial eucalypt species, most likely *E. dunnii*. Such a trial selection could potentially better highlight the role of silviculture inputs across time, before intraspecific competition is activated as a response to site characteristics. It is envisaged that silviculture treatments on marginal sites would account for variability for a much longer time frame as canopy closure would take longer to reach. In effect, the poorer the site, the more important the emphasis on good silviculture inputs as the sites could not buffer bad practices without serious consequences. Understanding the transition of main and interactive silviculture factors on differing site types, to the point of intraspecific competition,

would be much more meaningful in the design of specific silviculture regimes when any further silviculture applications simply become wasteful.

In conclusion, a much greater emphasis should be placed on the importance of understanding the role of water deficits, current basal area increment, rainfall distribution and when basal area increment would peak. As a final point, the attempt to determine the physiological status of trees by limited point measures of stomatal conductance and chlorophyll conductance was short-sighted and would not be recommended. Such physiological studies require simpler trial designs with recording instruments fitted with data logging capabilities. The measurement of leaf area index is more advisable and applicable under such large field experiments, and would more effectively explain the transition, especially when abiotic stressors are prevalent.

APPENDIX 1: FULL PRODUCTIVITY AND COSTS DATA FOR RESIDUE TREATMENTS

Compt	Rep	Species	Mulch Time minutes	Mulch Area m^2	Mulch Minutes/ha	Mulch R/ha	Mulch Trial average R/ha	Spread m^2	Spread Time minutes	Spread No Units	Spread Minutes/ha	Spread Unit/ha	Spread Rate/ha	Burn m^2	Burn Time minutes	Burn No Units	Burn Minutes/ha	Burn Unit/ha	Burn Rate/Ha
E013	Rep1	E.gran	28	1200	233.33	R 8 555.56	R 11 763.89	1200	27	14	3 150.00	6.56	918.75	1200	30	10	2 500.00	5.21	729.17
E013	Rep2	E.gran	23	1200	191.67	R 7 027.78	R 11 763.89	1200	30	10	2 500.00	5.21	729.17	1200	30	10	2 500.00	5.21	729.17
E013	Rep3	E.gran	47	1200	391.67	R 14 361.11	R 11 763.89	1200	55	8	3 666.67	7.64	1 069.44	1200	30	10	2 500.00	5.21	729.17
E013	Rep4	E.gran	56	1200	466.67	R 17 111.11	R 11 763.89	1200	69	8	4 600.00	9.58	1 341.67	1200	30	10	2 500.00	5.21	729.17
D010	Rep1	E.gran	50	1200	416.67	R 15 277.78	R 13 826.39	1200	25	16	3 333.33	6.94	972.22	1200	50	11	4 583.33	9.55	1 336.81
D010	Rep2	E.gran	50	1200	416.67	R 15 277.78	R 13 826.39	1200	12	16	1 600.00	3.33	466.67	1200	50	11	4 583.33	9.55	1 336.81
D010	Rep3	E.gran	49	1200	408.33	R 14 972.22	R 13 826.39	1200	13	16	1 733.33	3.61	505.56	1200	70	12	7 000.00	14.58	2 041.67
D010	Rep4	E.gran	32	1200	266.67	R 9 777.78	R 13 826.39	1200	13	16	1 733.33	3.61	505.56	1200	70	12	7 000.00	14.58	2 041.67
D01b	Rep1	E.dun	50	1200	416.67	R 15 277.78	R 17 951.39	1200	25	16	3 333.33	6.94	972.22	1200	40	11	3 666.67	7.64	1 069.44
D01b	Rep2	E.dun	58	1200	483.33	R 17 722.22	R 17 951.39	1200	12	16	1 600.00	3.33	466.67	1200	40	11	3 666.67	7.64	1 069.44
D01b	Rep3	E.dun	47	1200	391.67	R 14 361.11	R 17 951.39	1200	13	16	1 733.33	3.61	505.56	1200	40	11	3 666.67	7.64	1 069.44
D01b	Rep4	E.dun	80	1200	666.67	R 24 444.44	R 17 951.39	1200	13	16	1 733.33	3.61	505.56	1200	40	11	3 666.67	7.64	1 069.44
F026	Rep1	E.dun	50	1200	416.67	R 15 277.78	R 15 430.56	1200	25	16	3 333.33	6.94	972.22	1200	35	10	2 916.67	6.08	850.69
F026	Rep2	E.dun	58	1200	483.33	R 17 722.22	R 15 430.56	1200	12	16	1 600.00	3.33	466.67	1200	35	10	2 916.67	6.08	850.69
F026	Rep3	E.dun	49	1200	408.33	R 14 972.22	R 15 430.56	1200	13	16	1 733.33	3.61	505.56	1200	35	10	2 916.67	6.08	850.69
F026	Rep4	E.dun	45	1200	375.00	R 13 750.00	R 15 430.56	1200	13	16	1 733.33	3.61	505.56	1200	35	10	2 916.67	6.08	850.69
F017	Rep1	E.dun	47	1200	391.67	R 14 361.11	R 11 840.28	1200	25	16	3 333.33	6.94	972.22	1200	45	12	4 500.00	9.38	1 312.50
F017	Rep2	E.dun	48	1200	400.00	R 14 666.67	R 11 840.28	1200	12	16	1 600.00	3.33	466.67	1200	45	12	4 500.00	9.38	1 312.50
F017	Rep3	E.dun	45	1200	375.00	R 13 750.00	R 11 840.28	1200	13	16	1 733.33	3.61	505.56	1200	45	12	4 500.00	9.38	1 312.50
F017	Rep4	E.dun	15	1200	125.00	R 4 583.33	R 11 840.28	1200	13	16	1 733.33	3.61	505.56	1200	45	12	4 500.00	9.38	1 312.50

APPENDIX 2: MEAN SQUARE AND F PROB. VALUES FOR COMBINED TRIALS AT FULL ROTATION

Source of variation		Variate: MAI_Vol_99_ha		Variate: Sph_99		Variate: Dbh_99		Variate: Ht_99		Variate: DbhCV_99	
	d.f.	m.s.	F pr.	m.s.	F pr.	m.s.	F pr.	m.s.	F pr.	m.s.	F pr.
Site	3	40.7616	0.022	48.76526	<.001	14.50684	0.416	71.47591	0.001	41.00838	<.001
Slash_mgt	2	0.233483	0.909	12.19813	0.009	6.767564	0.199	0.700426	0.675	6.910466	0.002
Site.Slash_mgt	6	2.422893	0.912	2.133291	0.427	3.921231	0.918	1.754743	0.908	0.840944	0.065
RPV	1	1.217028	0.278	1.534699	0.142	0.395563	0.648	0.516559	0.342	1.321306	0.335
Hardening	1	0.419526	0.524	0.444972	0.428	0.073953	0.843	0.088256	0.694	2.589959	0.178
Insect	1	3.628758	0.062	2.942267	0.042	0.706854	0.541	1.295291	0.133	0.26501	0.666
Site.RPV	3	0.675954	0.58	2.908966	0.007	2.203113	0.322	1.011054	0.152	4.420821	0.027
Slash_mgt.RPV	2	3.366128	0.04	0.587991	0.437	1.437785	0.468	0.10037	0.839	1.464042	0.358
Site.Hardening	3	2.249874	0.091	1.23806	0.157	0.600224	0.812	0.248762	0.727	1.01612	0.543
Slash_mgt.Hardening	2	1.110984	0.342	2.481408	0.031	1.243443	0.518	0.983365	0.18	1.586066	0.328
RPV.Hardening	1	10.84473	0.001	0.326916	0.497	18.50546	0.002	1.750416	0.081	1.392923	0.323
Site.Insect	3	0.133641	0.942	0.889943	0.289	0.906355	0.696	0.516559	0.438	0.344862	0.866
Slash_mgt.Insect	2	0.977343	0.389	0.211123	0.742	0.524551	0.757	0.57756	0.364	1.057793	0.475
RPV.Insect	1	2.470644	0.123	0.081729	0.734	4.112133	0.141	2.427913	0.04	3.157159	0.137
Hardening.Insect	1	0.133951	0.719	0.73556	0.309	0.018918	0.922	0.030717	0.817	0.296202	0.648
Site.Slash_mgt.RPV	6	1.412372	0.227	0.727248	0.407	1.503139	0.573	0.254818	0.847	1.982333	0.216
Site.Slash_mgt.Hardening	6	1.232841	0.309	0.967884	0.228	0.861639	0.84	0.24184	0.862	0.442182	0.931
Site.RPV.Hardening	3	**3.58969**	**0.017**	0.672008	0.417	2.576318	0.254	0.346103	0.611	5.247293	0.012
Slash_mgt.RPV.Hardening	2	2.068172	0.137	1.069289	0.222	2.005331	0.347	2.62649	0.011	4.142836	0.056
Site.Slash_mgt.Insect	6	1.149432	0.354	0.174821	0.96	2.916846	0.163	0.89035	0.158	1.261416	0.503
Site.RPV.Insect	3	1.193462	0.327	0.753737	0.364	3.253934	0.162	0.68139	0.312	1.015122	0.543
Slash_mgt.RPV.Insect	2	0.821998	0.452	1.886579	0.071	2.115401	0.327	0.265201	0.628	2.345161	0.193
Site.Hardening.Insect	3	1.277182	0.296	0.09988	0.935	1.957176	0.376	0.789115	0.248	3.348056	0.072
Slash_mgt.Hardening.Insect	2	0.368054	0.7	0.619793	0.417	0.514232	0.762	0.310628	0.58	0.076858	0.947
RPV.Hardening.Insect	1	0.006201	0.938	5.230678	0.007	1.248603	0.417	0.061001	0.744	1.03783	0.393
Site.Slash_mgt.RPV.Hardening	6	0.600607	0.744	0.179346	0.958	1.06458	0.759	0.275152	0.821	1.495982	0.39
Site.Slash_mgt.RPV.Insect	6	1.13734	0.361	1.032962	0.192	0.576146	0.934	0.397586	0.651	1.384938	0.442
Site.Slash_mgt.Hardening.Insect	6	0.475028	0.837	0.074916	0.996	1.527216	0.563	0.144931	0.957	0.409742	0.942
Site.RPV.Hardening.Insect	3	1.145401	0.345	2.209732	0.026	3.212658	0.167	0.436955	0.513	0.795029	0.642
Slash_mgt.RPV.Hardening.Insect	2	1.697327	0.195	1.614166	0.104	0.729211	0.68	0.446906	0.457	2.464191	0.178
Site.Slash_mgt.RPV.Hardening.Insect	6	0.565569	0.771	0.191447	0.95	0.701694	0.896	0.105994	0.981	0.164446	0.994
Residual		12.22423		4.939529		19.96216		9.404054		3.601338	
Total		101.6114		99.92432		102.6503		101.1564		98.88681	

APPENDIX 3: MEAN SQUARE AND F PROB. VALUES FOR COMBINED TRIALS AT FULL ROTATION

Source of variation	Variate: BA_0		Variate: BA_12		Variate: BA_24		Variate: BA_36		Variate: BA_48		Variate: BA_99	
	m.s.	F pr.	m.s.	F pr.	m.s.	F pr.	m.s.	F pr.	m.s.	F pr.	m.s.	F pr.
Site stratum	0.00284487	**<.001**	11.7977	0.003	375.284	**<.001**	72.409	0.103	148.373	0.096	477.310	0.018
Residual	0.00004195		1.405		17.434		28.21		55.911		95.640	
Slash_mgt	0.00000083	0.961	11.8364	**<.001**	47.755	**<.001**	19.606	0.123	14.225	0.464	16.110	0.629
Site.Slash_mgt	0.00001444	0.659	1.6187	0.036	8.106	0.178	4.79	0.758	9.825	0.767	17.510	0.791
Residual	0.0000209		0.5931		4.926		8.565		17.930		34.040	
RPV	0.00437087	**<.001**	5.2869	**<.001**	12.965	0.005	15.191	0.035	14.052	0.164	34.870	0.121
Hardening	0.00024766	**<.001**	1.5423	0.01	4.621	0.091	14.948	0.036	1.005	0.709	0.250	0.896
Insect	0.00001228	0.432	0.095	0.52	5.343	0.069	11.028	0.072	14.905	0.152	63.690	0.036
Site.RPV	0.00084244	**<.001**	0.656	0.037	3.945	0.063	9.559	0.039	16.632	0.077	25.050	0.159
Slash_mgt.RPV	0.0000191	0.382	0.2133	0.395	0.766	0.620	3.168	0.393	14.758	0.132	42.160	0.055
Site.Hardening	0.0000739	**0.012**	0.4639	0.11	1.6	0.394	2.86	0.470	8.679	0.310	25.140	0.158
Slash_mgt.Hardening	0.0000142	0.489	0.0174	0.927	0.87	0.582	2.107	0.537	3.209	0.642	22.630	0.209
RPV.Hardening	0.00000072	0.848	0	0.996	0.039	0.875	2.191	0.422	19.828	0.099	104.740	0.007
Site.Insect	0.00004222	0.096	0.0124	0.983	1.317	0.483	0.727	0.886	0.644	0.966	1.390	0.962
Slash_mgt.Insect	0.00000646	0.722	0.0407	0.837	1.12	0.498	1.731	0.600	6.572	0.404	8.300	0.563
RPV.Insect	0.00000816	0.521	0.7501	0.071	1.504	0.333	4.457	0.252	7.632	0.305	32.090	0.137
Hardening.Insect	0.0000019	0.757	0.0196	0.77	0.843	0.469	1.174	0.556	0.385	0.818	5.880	0.523
Site.Slash_mgt.RPV	0.00001163	0.740	0.3784	0.132	1.352	0.537	2.788	0.552	5.091	0.646	12.330	0.527
Site.Slash_mgt.Hardening	0.00000744	0.894	0.184	0.568	2.183	0.230	6.182	0.094	8.659	0.307	23.230	0.143
Site.RPV.Hardening	0.00008206	**0.007**	0.1106	0.694	1.32	0.482	1.785	0.664	23.774	0.021	30.270	0.100
Slash_mgt.RPV.Hardening	0.00000494	0.779	0.0398	0.84	2.611	0.198	8.867	0.075	30.990	0.015	37.660	0.075
Site.Slash_mgt.Insect	0.00000576	0.941	0.1377	0.729	0.912	0.755	2.599	0.596	6.129	0.534	11.020	0.598
Site.RPV.Insect	0.00000651	0.805	0.0416	0.909	0.152	0.811	2.144	0.594	6.019	0.477	12.970	0.441
Slash_mgt.RPV.Insect	0.00000724	0.694	0.0451	0.821	2.451	0.218	3.966	0.311	12.261	0.185	20.370	0.245
Site.Hardening.Insect	0.00002654	0.261	0.2308	0.389	1.219	0.517	0.513	0.929	7.782	0.359	10.760	0.525
Slash_mgt.Hardening.Insect	0.0000011	0.946	0.0154	0.935	1.249	0.460	5.575	0.194	13.876	0.148	5.680	0.674
RPV.Hardening.Insect	0.0000009	0.831	0.1189	0.472	5.779	0.059	6.959	0.153	14.927	0.152	22.620	0.211
Residual	0.0000198		0.2288		1.602		3.384		7.225		14.400	
Total	**0.00873682**		**37.8796**		**509.268**		**247.483**		**491.298**		**1208.11**	

Source of variation	Variate: BA_0		Variate: BA_12		Variate: BA_24		Variate: BA_36		Variate: BA_48		Variate: BA_99	
Source of variation												
Site_stratum	32.5618474		31.14526		73.69087		29.25817		30.2002		39.50882	
Residual	0.48015182		3.70912		3.423345		11.39876		11.38026		7.916498	
Slash_mgt	0.00950002		31.24743		9.377185		7.92216		2.895391		1.333488	
Site.Slash_mgt	0.16527753		4.273276		1.591696		1.935486		1.999805		1.449371	
Residual	0.23921747		1.56575		0.967271		3.460844		3.649516		2.817624	
RPV	50.0281567		13.95712		2.545811		6.138199		2.860179		2.886327	
Hardening	2.83466982		4.071585		0.907381		6.040011		0.20456		0.020693	
Insect	0.14055457		0.250795		1.049153		4.456064		3.0338		5.271871	
Site.RPV	9.64240994		1.731803		0.774641		3.862488		3.385318		2.073487	
Slash_mgt.RPV	0.21861501		0.5631		0.150412		1.280088		3.00388		3.489748	
Site.Hardening	0.84584551		1.22467		0.314176		1.155635		1.766545		2.080936	
Slash_mgt.Hardening	0.16253053		0.045935		0.170833		0.851372		0.653168		1.873174	
RPV.Hardening	0.00824098		0		0.007658		0.885313		4.03584		8.66974	
Site.Insect	0.48324219		0.032735		0.258606		0.293758		0.131081		0.115056	
Slash_mgt.Insect	0.07393995		0.107446		0.219923		0.699442		1.337681		0.687024	
RPV.Insect	0.09339783		1.980222		0.295326		1.800932		1.553436		2.656215	
Hardening.Insect	0.02174704		0.051743		0.165532		0.474376		0.078364		0.486711	
Site.Slash_mgt.RPV	0.13311479		0.998955		0.265479		1.126542		1.036235		1.020602	
Site.Slash_mgt.Hardening	0.08515684		0.48575		0.428654		2.497949		1.762474		1.922838	
Site.RPV.Hardening	0.13311479		0.998955		0.265479		1.126542		1.036235		1.020602	
Slash_mgt.RPV.Hardening	0.08515684		0.48575		0.428654		2.497949		1.762474		1.922838	
Site.Slash_mgt.Insect	0.93924334		0.291978		0.259196		0.721262		4.839018		2.505567	
Site.RPV.Insect	0.08515684		0.48575		0.428654		2.497949		1.762474		1.922838	
Slash_mgt.RPV.Insect	0.13311479		0.998955		0.265479		1.126542		1.036235		1.020602	
Site.Hardening.Insect	0.08515684		0.48575		0.428654		2.497949		1.762474		1.922838	
Slash_mgt.Hardening.Insect	0.93924334		0.291978		0.259196		0.721262		4.839018		2.505567	
RPV.Hardening.Insect	0.08515684		0.48575		0.428654		2.497949		1.762474		1.922838	
Residual	0.08515684		0.48575		0.428654		2.497949		1.762474		1.922838	
Total	**101**		**102**		**100**		**102**		**96**		**103**	

REFERENCES

- ABRAF – Brazilian Association of Forest Plantation Producers, 2013. ABRAF Statistical Year Book – Base Year 2012. Brasília 150.
- Adams MA, Attiwill PM (1986) Nutrient cycling and nitrogen mineralization in eucalypt forests of south-eastern Australia. II. Indices of nitrogen mineralization. *Plant and Soil* 92: 341 – 362.
- Adams PR, Beadle CL, Mendham NJ and Smethurst PJ (2003). The impact of timing and duration of grass control on growth of *Eucalyptus globulus* Labill plantation. New Forests 26: 147 – 165.
- Agriculture Research Council (ARC) (2020). Climate data 2010 – 2019: Cedara Agriculture Research Centre. Cedara Agriculture Research Centre
- Alvares CA, Stape JL, Sentelhas PC, Gonçalves JLM, Sparovek G. (2013a). Köppen's climate classification map for Brazil. *Meteoro-logische Zeitschrift* 22: 711–728.
- Anderson CA (1982). The effect of calcium on the germination, growth and mineral nutrition of acidic and calcareous populations of *Eucalyptus obliqua* L'Hérit. *Plant and Soil* 69: 213-223.
- Atkinson PR and MacLennan L (1997). Recommendations, practices and notes for the control of pests and diseases in commercial forestry in South Africa. ICFR Bulletin Series No.01/97: 1 - 20.
- Attiwill, PJ (1980). Nutrient cycling in a Eucalyptus obliqua (L'Hérit) forest. III. Growth biomass and net primary production. *Australian Botany* 27: 439-458.
- Aussenac G, Guehl JM, Kaushal P, Granier A, and Grieu P (1988). Critères physiologiques pour l'évaluation de la qualité de plants forestiers avant plantation. *Rev For. Fr*. 40S:131 -139.
- Baker TG, Attiwill PM (1985). Above ground nutrient distribution and cycling in *Pinus radiata* D.Don and *Eucalyptus obliqua* (L'Hérit) forests in south-eastern Australia. *Forest Ecology and Management* 13: 41-52.
- Barros NF, Neves JCL, Novais RF (2000). Recommendação de fertilizantes minerais em plantios de eucalipto. In: Gonçalves JLM, Benedetti V (Eds.), Nutrição e fertilização florestal. Piracicaba, IPEF, 269 286.
- Barros NF, Novais RF, Neves JCL, Leal JCL (1992). Fertilizing eucalypt plantations on the Brazilian savannah soils. *South African Forestry Journal* 160: 7 – 12.

- Barry KM, Pinkard EA (2013). Growth and photosynthetic responses following defoliation and bud removal in eucalypts. *Forest Ecology and Management* 293: 9 – 16.
- Bartlett MK, Scoffoni C (2012). The determinants of leaf turgor loss point and prediction of drought tolerance of species and biomes: a global meta-analysis. *Ecology Letters* **15**: 393–405.
- BASF Product catalogue (2014). http://www.agro.basf.co.za.
- Battie-Laclau P, Laclau JP, Domec JC, Christina M, Bouillet JP, Cassia Piccolo M, Gonçalves JLM, Moreira R, Krusche AV, Bouvet JM, Nouvellon Y (2014). Effects of potassium and sodium supply on drought-adaptive mechanisms in *Eucalyptus grandis* plantations. *New Phytologist* 203: 401–413.
- Beadle NCW, White GJ (1968). The mineral content of the trunks of some Australian woody plants. *Proceedings Ecological Society of Australia* 3: 348-355.
- Bell DT, Ward SC (1984). Seasonal changes in the foliar macronutrients (N, P, K, Ca, and Mg) in *Eucalyptus saligna* Sm. and *E. wandoo* Blakely growing in rehabilitated bauxite mine soils of the Darling Range, Western Australia. *Plant and Soil* 81: 377 - 388.
- Benayas JMR, Camacho-Cruz A (2004). Performance of *Quercus ilex* saplings planted in abandoned Mediterranean cropland after long-term interruption of their management. *For. Ecol. Manag* 2004, 194: 223 – 233.
- Bengough G, McKenzie BM, Hallett PD, Valentine T (2011). Root elongation, water stress and mechanical impedance: A review of limiting stresses and beneficial root tip traits. *J. Exp. Bot* 2011, 62: 59 – 68.
- Binkley D. and Giardina C (1998). Why do species affect soils? The warp and woof of tree – soil interactions. *Biogeochemistry* 42: 89-106.
- Binkley D, Stape JL, Ryan MG (2004). Thinking about efficiency of resource use in forests. *For. Ecol. Manage*. 193, 5–16.
- Binkley D, Campoe OC, Alvares C, Carneiro RL, Cegatta I, Stape JL (2017). The interactions of climate, spacing and genetics on clonal *Eucalyptus* plantations across Brazil and Uruguay. *For. Ecol. Manage*. 405, 271–283.
- Binotto AF, Alessandro DL, Sidinei JL (2010). Correlations between growth variables and the Dickson Quality Index in forest seedlings. Cerne, Lavras v.16, n4, p 457-464, out./dez 2010.
- Bloom AJ, Chapin FS, Mooney H (1985). Resource limitations in plants – an economic analogy. Ann. *Rev. Ecol. Syst* 1985, 16: 363 – 392.

- Bold A (2018) Rainfall data for Hilton KZN. Mondi SA internal document.
- Booth TH (2013). Eucalypt plantations and climate change. *Forest Ecology and Management*. 301: 28 – 34.
- Boreham GR, Pallet RN (2009). The influence of tree improvement and cultural practices on the productivity of Eucalyptus plantations in temperate South Africa. *Southern Forests 2009, 71(2):* 85 – 93.
- Bouillet JP, Nzila JP, Laclau JP, Ranger J (2000). Effects of site management in *Eucalyptus grandis* on the equatorial zone, on the coastal plains of the Congo. In: Nambiar EKS, Cossalter C, Tjarks A and Ranger J (Eds.). Site management and productivity in tropical plantation forests: workshop proceedings, 7 – 11 December 1999, Kerala, India Center for International Forestry Research, Bogor. 11 - 20.
- Bradstock, R (1981). Biomass in an age series of *Eucalyptus grandis* plantations. *Australian Forests Research.* 11:111-127.
- Brady NC, Weil RR (1999). *The nature and properties of soils* (12th edn). Englewood Cliffs: Prentice-Hal Inc. pp. 189-228.
- Brantburg, PO, Lundvist, H, Bengtsson, J (2000). Changes in the forest-floor chemistry caused by a birch admixture in Norway spruce stands. *For. Ecol. Manage*. 130: 253-264.
- Brissette JC, Chambers JL (1992). Leaf water status and root system water flux of shortleaf pine (*Pinus echinata* Mill.) seedlings in relation to new root growth after transplanting. *Tree Physiology* 11: 289-303
- Buerkert A, Bationo A, and Dossa K (2000). Mechanisms of residue mulch-induced cereal growth increases in West Africa. *Soil Science Society American Journal* 64:346-358.
- Burdett AN (1990). Physiological processes in plantation establishment and the development of specifications for forest planting stock. *Canadian Journal of Forest Research* 20:415-425.
- Campbell KA, Hawkins CDB (2004). Effect of seed source and nursery culture on paper birch (*Betula papyrifera*) uprooting resistance and field performance. *For Ecol Manag* 196:425–433.
- Campion JM, Nkosana M, Scholes MC (2006). Biomass and N and P pools in above- and below-ground components of an irrigated and fertilised *Eucalyptus grandis* stand in South Africa. *Australian Forestry* 69: 48–57.

- Čatský J. (1965). Water Saturation Deficit and Photosynthetic Rate as Related to Leaf age in the Wilting Plant. In: Slavík B. (Eds) Water Stress in Plants. Springer, Dordrecht. pp 203 - 209.
- Causton DR, (1977). A Biologist's Mathematics. Edward Arnold. London. 326 p.
- Causton, DR, Venus, JC (1981). The Biometry of Plant Growth. Edward Arnold, London. 307 pp.
- Chaney WR, Kozlowski TT (1969). Diurnal Expansion and Contraction of Leaves and Fruits of English Morello Cherry. *Annals of Botany.* New Series, Vol. 33, No. 133 (November 1969), pp. 991-999.
- Chapin FS, Kedrowski RA (1983). Seasonal changes in nitrogen and phosphorus fractions and autumn retranslocation in evergreen and deciduous taiga trees. *Ecology* 64: 376-391.
- Chen Q, Gong P, Baldocchi D, Tian YQ (2007). Estimating basal area and stem volume for individual trees from lidar data. *Photogramm Eng Remote Sens* 73: 1355-1365.
- Christina M, Laclau JP, Gonçalves JLM, Jourdan C, Nouvellon Y, Bouillet JP (2011). Almost symmetrical vertical growth rates above and below ground in one of the world's most productive forests. *Ecosphere* 3: 124–130.
- Chukwu O, Osho JSA (2018). Basal Area-Stump Diameter Models for *Tectona grandis* Linn. F. Stands in Omo Forest Reserve, Nigeria. Journal of Forest and Environmental Science. Vol. 34, No.2 119 -125.
- Clark LJ, Whalley WR, Barraclough PB (2003). How do roots penetrate strong soil? Plant Soil 2003, 255: 93 – 104.
- Clarkson DT, Hanson, JB (1980). The mineral nutrition of higher plants. *Annual Review of Plant Physiology* 31:239-298.
- Cedara Agriculture Research Centre (2008) Climate data – Hilton, KZN, Midlands. AgroClimatology. ARC-ISCW. Pretoria. 3 pp.
- Close DC, Davidson NJ, Churchill KC, Grosser P (2005). Evaluation of establishment techniques on *Eucalyptus nitens* and *E. pauciflora* in the Midlands of Tasmania. *Ecological Management and Restoration* 6(2): 149-151.
- Coetzee J (1999). Growth prediction for short rotation *E. grandis* crops. ICFR Bulletin Series 9/99: 10 pp.

- Correia MJ, Torres F, Pereira SJ (1989). Water and nutrient supply regimes and the water relations of juvenile leaves of *Eucalyptus globulus*, *Tree Physiology*. 5: 459–471.
- Costa e Silva F, Shvaleva, A. Maroco JP, Almeida MH, Chaves MM, Pereira JS (2004). Responses to water stress in two *Eucalyptus globulus* clones differing in drought tolerance. *Tree Physiology* 24: 1165 – 1172.
- Cowan IR, Farquhar GD (1977). Stomatal function in relation to leaf metabolism and environment. *Symposia of the Society for experimental Biology* 31: 475-505.
- Cregg BM, (1994). Carbon allocation, gas exchange, and needle morphology of *Pinus ponderosa* genotypes known to differ in growth and survival under imposed drought, *Tree Physiology.* 14: 883–898.
- Cromer RN (1984). The influence of nutrition on growth and photosynthesis in *Eucalyptus.* In: Grey DC, Schönau APG, Schutz CJ, Van Laar A (Eds.) Site and productivity of fast-growing plantations. Proceedings vol. 2, IUFRO symposium, Pretoria and Pietermaritzburg, South Africa. South African Forest Research Institute, Dept. of Environment Affairs, Pretoria, pp 669-678.
- Cromer RN (1996). Silviculture of eucalypt plantations in Australia. In: Attiwill PM, Adams MA (Eds.) Nutrition of eucalypts. CSIRO Publishing, Collingwood, pp 259-273.
- Cromer RN, Cameron D, Cameron JN, Flinn DW, Neilson WA, Raupach M, Snowdon P, Waring HD (1981). Response of eucalypt species to fertilizer applied soon after planting at several sites. *Australian Forestry* 44:3-13.
- Cromer RN, Cameron DM, Rance SJ, Ryan PA, Brown M (1993). Response to nutrients in *Eucalyptus grandis* 1. Biomass accumulation. *Forest Ecology Management* 62: 211 – 230.
- Cromer RN, Jarvis PG (1990). Growth and biomass partitioning in *Eucalyptus grandis* seedlings in response to nitrogen supply. *Australian Journal of Plant Physiology* 17:503-515.
- Cromer RN, Wheeler AM, Barr NJ (1984). Mineral nutrition and growth of *Eucalyptus* seedlings. *New Zealand Journal of Forestry Science* 14: 229-239.
- Crous JW (2016). Use of hydrogels in the planting of industrial wood plantations. *Southern Forests* 79: 1-17.
- Crous, JW, Morris AR, Scholes MC, 2008. Growth and foliar nutrient response to recent applications of phosphorus (P) and potassium (K) and to residual P and K fertiliser

applied to the previous rotation of Pinus patula at Usutu, Swaziland. *Forest Ecology and Management* 256: 712–721.

- Crous JW, Sale G, Naidoo T (2019). The influence of species, tree improvement and cultural practices on rotation end fibre production of *Eucalyptus* pulpwood plantations in South Africa. *Southern Forests* 2019, 81(4): 307 - 317.
- Curtis (2012) South African Forestry Handbook (Eds Bredenkamp BV, Upfold S), Chapter 2.11. pp 130. South African Institute of Forestry, Menlo Park, South Africa.
- Da Costa GD (2008) Mulching as an alternate slash management treatment – A Mondi experience. Wood SA, March 2008: 10 -16.
- Darrow WK (1995). Selection of *Eucalyptus* spp. for cold and dry areas in South Africa. In: Potts BM, Borralho JB, Reid RN, Cromer WN, Tibbits WN and Raymond CA (Eds), *proceedings of the CRC-IUFRO: Eucalyptus plantations: Improving fibre yield and quality Conference, 19-24 February,* Hobart.
- Davis A, Jacobs D (2005). Quantifying system quality of nursery plants and relationship to out planting performance. *New Forests* 30:295-311.
- Dawson TE (1996). Determining water use by trees and forests from isotopic, energy balance and transpiration analyses: the role of tree size and hydraulic lift. *Tree Physiology* 16: 263 – 372.
- De Barros NF, De Novais RF (1996). Eucalypt nutrition and fertilizer regimes in Brazil. In*:* Attiwill PM, Adams MA (Eds.) Nutrition of eucalypts*.* CSIRO Publishing, Collingwood, pp 335-355.
- Decagon (2009). Decagon Devices, Inc. http://www.decagon.com. Accessed (July 2010).
- Dell B (1996). Diagnosis of nutrient deficiencies in eucalypts. In: Attiwill PM, Adams MA (Eds.) Nutrition of eucalypts*.* CSIRO Publishing, Collingwood, pp 417- 440.
- Dell B, Malajczuk N, Xu D, Grove TS (2001). Nutrient disorders in plantation eucalyptus (2nd edn). ACIAR Monograph 74, Australian Centre for International Agricultural Research, Canberra, Australia, pp. 104.
- Dell B, Wallace IM (1983). Periodicity of fine root growth in jarrah (*Eucalyptus marginata* Donnex Sm.). *Australian Journal of Botany* 31: 247-254.
- Demchik MC, Sharpe WE (2000). The effects of soil nutrition, soil acidity and drought on northern red oak (*Quercus rubra* L.) growth and nutrition on Pennsylvania sites with high and low mortality. *Forest Ecology and Management* 136: 199 – 207.

- Dighton J, Jones HE, Poskitt JM, (1993). The use of nutrient bioassays to assess the response of *Eucalyptus grandis* to fertilizer application. Interactions between nitrogen, phosphorus, and potassium in seedling nutrition. *Canadian Journal of Forest Research* 23*:* 1-6.
- Dovey SB (2005). Simple ratios to estimate biomass components and nutrient contents in mature stands of some important commercial plantation species. *ICFR Bulletin 13/2005*, Institute for Commercial Forestry Research, Pietermaritzburg, South Africa. 14pp.
- Du Toit B (2003). Effects of site management operations on the nutrient capital of a eucalypt plantation system in South Africa. *Southern African Forestry Journal*, 199: 15-26.
- Du Toit B (2008). Effects of site management on growth, biomass partitioning and light use efficiency in a young stand of Eucalyptus grandis in South Africa. Forest Ecology and Management. *Forest Ecology and Management*, 255 (2008) 2324–2336.
- Du Toit B, Dovey SB (2005). Effect of site management on leaf area, biomass development and stand growth efficiency of a young stand of *Eucalyptus grandis* in South Africa. *Can. J. For. Res.* 35 (4), 891–900.
- Du Toit B, Esprey, LJ, Job RA, Fuller GF and Dovey SD (2000). Effects of site management in *Eucalyptus grandis.* In: Nambiar EKS, Cossalter C and Tjarks A (Eds.). Site management and productivity in tropical plantation forests: workshop proceedings, 7 – 11 December 1999, Kerala, India Center for International Forestry Research, Bogor. 21-30.
- Du Toit B Dovey SB Smith CW, 2008. Effects of slash and site management treatments on soil properties, nutrition and growth of a Eucalyptus grandis plantation in South Africa. In Nambiar, EKS. (ed.) Site Management and Productivity in Tropical Plantation Forests: Proceedings of Workshops in Piracicaba (Brazil) 22-26 November 2004 and Bogor (Indonesia) 2-9 November 2006. Center for International Forestry Research (CIFOR), Bogor, Indonesia. pp 63-78.
- Du Toit B, Smith CW, Little KM, Boreham G, Pallett RN. 2010. Intensive, site-specific silviculture: manipulating resource availability at establishment for improved stand productivity. A review of South African research. *Forest Ecology and Management* 259: 1836–1845.
- Du Toit, B and Scholes, MC (2002). Fire intensity and nutrient dynamics: Implications for management and research. *SAIF Symposium.* Nelspruit, South Africa. 28 May 2003.

- Du Toit, B and Scholes, MC (2002). Nutritional sustainability of eucalyptus plantations. *Southern African Forestry Journal*, 195: 63-72.
- Edwards DR and Dixon MA (1995). Mechanisms of drought response in *Thuja occidentalis* L.II. Post-conditioning water stress and stress relief. *Tree Physiology* 15:129-133.
- Elledge J, Barlow B (2012). Basal Area: A measure made for management. Alabama Cooperative Extension System. ANR-1371. https://store.aces.edu/DisplayImage.aspx?ProductID=13433. Accessed (April, 2020).
- Ellis F (1995). Drought resistance of *Eucalyptus* species/provenances on sandy soils along the dry South African Cape West Coast: a case study. In: Schulte A, Ruhiyat D (eds), *Proceedings of the International Congress on Soils of Tropical Forest Ecosystems, Third Conference on Forest Soils, 29 October–3 November, Balikpapan, Indonesia.* Samarinda: Mulawarman University Press. pp 106–114.
- Ellis F (2000). Soils. South African Forestry Handbook. Vol 1. Pretoria. South African Institute of Forestry, Pretoria.
- Erdle T. (2019). Measurement of Tree Basal Area and Volume. (http://ifmlab.for.unb.ca/People/Kershaw/Courses/For1001/Erdle_Version/TAE-BasalArea&Volume.pdf. Accessed (July 2020).
- Evans J (1999). Sustainability of Forest Plantations. A review of evidence concerning the narrow-sense sustainability of planted forests. The Department for International Development (DFID), London.
- Evans J and Turnbull J (2004). Plantation Forestry in the Tropics. Third edition. Oxford University Press, New York. 385.
- Fan S, Blake TJ, Blumwald E (1994). The relative contribution of elastic and osmotic adjustment to turgor maintenance of woody plants, *Physiol. Plant*. 90: 414–419.
- Ferreira FAS (1986). A interação nitrato, fosfato e sulfato na absorção de fosfato e de sulfato no crescimento de eucalipto e no seu metabolismo de nitrato e sulfato. Universidade Federal de Viçosa, Viçosa.
- Fey M (2010). Soils of South Africa. Their distribution, properties, classification, genesis, use and environmental significance. Cambridge University Press. Cambridge. 287.
- Fife DN, Nambiar EKS (1984). Movement of nutrients in radiata pine needles in relation to the growth of shoots. *Annals of Botany* 50: 817-829.

- Fife, DN and Nambiar EKS (1995). Effect of nitrogen on growth and water relations of radiate pine families. *Plant and Soil* 168 – 169: 279 – 285.
- Fisher RA (1921). Some remarks on the methods formulated in a recent article on "The quantitative analysis of plant growth". Ann. Appl. Biol. 7,367–372.
- Fisher RF and Binkley D (2000). Ecology and management of Forest Soils, third ed. Wiley, 489 pp. John Wiley and Sons, Inc., New York.
- Flinn DW (1978). Comparison of establishment methods for *Pinus radiata* on a former *Pinus pinaster* site. *Australian Forestry* 41(3): 167-176.
- Folster H, Khanna PK (1997). Dynamics of nutrient supply in plantation soils. In Nambiar, EKS and Brown, AG (Eds.) *Management of soil, nutrients and water in tropical plantation forests*. ACIAR Monograph No. 43, Australian Centre for International Agricultural Research, Canberra, pp. 339 -378.
- Fonseca EP *et al*. (2002). Padrão de qualidade de mudas de *Trema microcantha* (L.) Blume, produzidas sob diferentes periodos de sombreamento. Revista Árvore, Viçosa, vol 26, no.4: 515-523.
- Forestry South Africa (2017). Abstract of South African Forestry facts for the year 2015/2015. Dept. Agriculture, Forestry & Fisheries.
- Forrester DI, Theiveyanathan S, Collopy JJ, Marcar NE (2010). Enhanced water use efficiency in a mixed *Eucalyptus globulus* and *Acacia mearnsii* plantation. *Forest Ecology and Management* 259 (2010) 1761 – 1770.
- Fotelli MN, Radoglou KM and Constantinidou HIA (2000). Water stress responses of seedlings of four Mediterranean oak species. *Tree Physiology* 20: 1065 – 1075.
- Franks PJ, Drake PL, Froend RH (2007). Anisohydric but isohydrodynamic: seasonally constant plant water potential gradient explained by a stomatal control mechanism incorporating variable plant hydraulic conductance. *Plant, cell & Environment* 30:19 – 30.
- Fyles JW, Cote, B (1994). Forest floor and soil nutrient status under Norway spruce and red pine in Southern Quebec. *Can. J. For. Res*. 23: 358-361.
- Gammon J, Surfus JS (1999). Assessing leaf pigment content and activity with a reflectometer. *New Phytologist* 143: 105 – 117.
- Gardner WR (1965). Dynamic aspects of water availability to plants. *Soil Sci*. 89: 63.

- Gardner WR and Ehlig CF (1965). Physical aspects of the internal water relations of plant leaves. Plant Physiol. 40, 705.
- Gaudet CL, Keddy PA (1988). A comparative approach to predicting competitive ability from plant traits. *Nature* 334: 242 - 243.
- George BH, Brennan PD (2002). Herbicides are more cost effective than alternative weed control methods for increasing early growth of *Eucalyptus dunnii* and *Eucalyptus saligna*. *New Forest* 24:147 – 163.
- Giliberto J, Estay H (1978). Seasonal water stress in some Chilean matorral shrubs. Bot. Gaz. 1978, 139: 236 -240.
- Gomes JM *et al.* (2002). Parâmetros morfólogicos na avaliação da qualidade de mudas de *Eucalyptus grandis*. Revista Árvore, Viçosa, vol 26, no.6: 655-664.
- Gomez KA, Gomez, AA (1984). Statistical Procedures for Agricultural Research Second Edition. An international Rice Research Institute Book. Wiley-interscience Publication John Wiley & Sons, New York.
- Gonçalves JLM Alvares CA, Higa AR, Silva LD, Alfenas AC, Stahl J, Ferraz SFB, Lima WP, Brancalion PHS, Hubner A (2013). Integrating genetic and silvicultural strategies to minimize abiotic and biotic constraints in Brazilian eucalypts plantations. *Forest Ecology and Management* 301: 6 – 27.
- Gonçalves JLM, Alvares CA, Rocha JHT, Brandani C, Hakamada R (2017). Eucalypt plantation management in regions of water stress. *Southern Forests* 79(3) 169-183.
- Gonçalves JLM, Barros NF, Nambiar EKS and Novais RF (1997). Soil and stand management for short-rotation plantations. In: Nambiar EKS and Brown AG (Eds.). Management of Soil, Water and Nutrients in Tropical Plantation Forests. ACIAR Monograph 43, Canberra, 379 – 418.
- Gonçalves JLM, Mello SLM (2004). The root system of trees. In: Gonçalves JLM, Benedetti V (Eds), *Forest nutrition and fertilization.* Piracicaba: IPEF. pp 223–267.
- Gonçalves JLM, Poggiani F, Stape JL, Serrano MIPS, Mello SLM, Mendes KCFS, Gava GL and Benedetti V (1999). Eucalypt plantations in the humid tropic: São Paulo, Brazil. In; Nambiar EKS, Cossalter C and Tjarks A (Eds.). Site management and productivity in tropical plantation forests: workshop proceedings, 16-20 February 1998, Pietermaritzburg, South Africa. Center for International Forestry Research, Bogor. 5 – 20.

- Gonçalves JLM, Stape JL, Benedetti V, Fessel VAG, and Gava JL (2000). Reflexos do cultivo mínimo e intensivo do solo em sua fertilidade e nutrição das árvores. In: Gonçalves JLM, Benedetti V (Eds.), Nutrição e fertilização florestal. Piracicaba, IPEF, 1 – 57.
- Gonçalves JLM, Stape JL, Laclau JL, Smethurst P, Gava JL (2004). Silvicultural effects on the productivity and wood quality of eucalypt plantations. *Forest Ecology and Management* 193: 45 – 61.
- Gonçalves JLM, Stape JL, Laclau JP, Bouillet JP and Ranger J (2008). Assessing the effects of early silvicultural management on long-term site productivity of fast growing eucalypt plantations: the Brazilian experience. *Southern Forests* 70(2) 1 – 14.
- Gonçalves JLM, Stape JL, Wichert MCP, and Gava JL (2002). Manejo de residues vegetais e preparo do solo. In: Gonçalves JLM, Stape JL (Eds.), Conservação e cultivo de solos para plantações florestais. Piracicaba, IPEF, 131 – 204.
- Gonçalves JLM. 2002. Principais solos usados para plantações florestais. In: Gonçalves JLM, Stape JL (Eds), *Conservação e cultivo de solos para plantações florestais*. Piracicaba: IPEF. pp 1–45.
- Grier CC, Elliot KJ, McCullough DG (1992). Biomass distribution and productivity of *Pinus edulis - Juniperus monosperma* woodlands of north-central Arizona. *Forest Ecology and Management* 50: 331 -350.
- Grime JP, Thompson K, Hunt R, Hodgson JG, Cornelissen JHC, Rorison IH, Hendry GAF, Ashenden TW, Askew AP, Band SR, Booth RE, Bossard CC, Campbell BD, Cooper JEL, Davison AW, Gupta PL, Hall W, Hand DW, Hannah MA, Hillier SH, Hodkinson DJ, Jalili A, Liu Z, Mackey JL, Matthews N, Mowforth MA, Neal AM, Reader RJ, Reiling K, Ross-Fraser AM, Spencer RE, Sutton F, Tasker DE, Thorpe PC, Whitehouse J (1997). Integrated screening validates primary axes of specialisation in plants. *Oikos* 79: 259 - 281.
- Grosman DM, Upton WW (2006). Efficacy of systemic insecticides for protection of loblolly pine against southern engraver beetles (Coleoptera: Curculionidae: Scolytinae) and woodborers (Coleoptera: Cerambycidae). *Journal of Economic Entomology* 99: 94 – 101.
- Grossnickle SC (2005). Importance of root growth in overcoming planting stress. *New Forest* 30:273–294.

- Grove TS (1990). Twig and foliar nutrient concentrations in relation to nitrogen and phosphorus supply in a eucalypt (*Eucalyptus diversicolor* F. Muell.) and an understorey legume *Bossiaea laidlawiana* Tovey and Morris. *Plant and Soil* 126: 265-275.
- Grove TS, Malajczuk N (1992). Nodule production and nitrogen fixation (acetylene reduction) by an understorey legume (*Bossiaea laidlawiana*) in *Eucalyptus* forest. *Journal of Ecology* 80: 303-314
- Grove TS, Thomson BD and Malajczuk N (1996). Nutrition physiology of eucalypts: uptake, distribution and utilization. In*:* Attiwill PM, Adams MA (Eds.) Nutrition of Eucalypts*.* CSIRO Publishing, Collingwood, pp 77 – 108.
- Guarnaschelli AB, Garau AM, Lemcoff JH (2001). Tissue water relations in *Eucalyptus globulus* subsp. *maidenii,* in: Proceedings IUFRO international symposium Developing eucalypts for the future, Valdivia, Chile, 2001, p. 65.
- Guarnaschelli AB, Lemcoff JH, Prystupa P, Basci S (2003). Responses to drought preconditioning in *Eucalyptus globulus* Labill. Provenances. *Trees* 17: 501-509.
- Guarnaschelli AB, Prystupa P, Lemcoff JH (2006). Drought conditioning improves water status, stomatal conductance and survival of *Eucalyptus globulus* subsp. b*iocostata* seedlings. *Ann. For.* Sci 63 941 - 950.
- Guehl JM, Clement, A, Kaushal, P and Aussenac, G (1993). Planting stress, water status and non-structural carbohydrate concentrations in Corsican pine seedlings. *Tree Physiology* 12:173-183.
- Gutschick VP, BassiRad (2003). Extreme events as shaping physiology, ecology and evolution of plants: toward a unified definition and evaluation of their consequences. *New Phytologist* 160: 21 – 42.
- Hakamada RE, Hubbard RM, G Gonçalves Moreira, JL Stape, O Campoe, SF de Barros Ferraz (2020). Influence of stand density on growth and water use efficiency in *Eucalyptus* clones. *Forest Ecology and Management 466* (2020). 1 - 8.
- Hamamishi ET, Thomas BR, Campbell MM (2012). Drought induces alterations in the stomatal development program in *Populus*. *Journal of Experimental Botany* 63: 4959–4971.
- Hamer JJ, Veneklaas EJ, Renton M, Poot P (2016). Links between soil texture and root architecture of *Eucalyptus* species may limit distribution ranges under future climates. *Plant Soil* 403, 217–229.

- Hamrick JL (2004). Response of forest trees to global environmental changes. *Forest Ecology and Management* 197: 323 – 335.
- Harrison AF, Helliwell DR (1979). A bioassay for comparing phosphorus availability in soils. Journal of Applied Ecology 16: 491-505.
- Harwood CE, Nambiar EKS (2014). Productivity of acacia and eucalypt plantations in Southeast Asia. 2. Trends and variations. *International Forestry Review* 16: 249–260.
- Hastings FL, Holsten EH, Shea PJ, Werner RA (2001). Carbaryl: a review of its use against bark beetles in coniferous forests of North America. *Environmental Entomology* 30: 803-810.
- Hechter U, (2018). The impact of re-establishment practices on tree survival, growth and uniformity in South African eucalypt plantations, South Africa. Un*published MSc thesis*, Nelson Mandela University, South Africa.
- Herbert MA (1996). Fertilisers and eucalypt plantations in South Africa. In*:* Attiwill PM, Adams MA (Eds.) Nutrition of eucalypts. CSIRO Publishing, Collingwood, pp 303-325.
- Herbert MA (2000). Eucalypt and wattle species. South African Forestry Handbook 2000. Vol. 1. The Southern African Institute of Forestry, Pretoria.
- Herbert MA, Schönau, APG (1989). Fertilising commercial forest species in Southern Africa: research, progress, and problems. Southern African Journal of Forestry 151: 58 – 70.
- Herbert, MA (1984). Variation in growth of and responses to fertilizing black wattle with nitrogen, phosphorus, potassium and lime over three rotations. In Grey, DC, Schönau, APG, Schutz, CJ and Van Laar, A (Eds.) *IUFRO Symposium on site productivity of fast growing plantations*, Pretoria and Pietermaritzburg, South Africa, April 1994. pp. 907-920.
- Hernández E, Vilagrosa A, Luis VC, Llorca M, Chrino E, Vallejo VR (2009). Root hydraulic conductance, gas exchange and leaf water potential in seedlings of *Pistacia lentiscus* L. and *Quercus suber* L. Grown under different fertilization and light regimes. *Environ. Exp. Bot*. 2009, 67: 269 – 276.
- Hertel D, Strecker T, Muller-Haubold H, Leuschner C (2013). Fine root biomass and dynamics in beech forests across a precipitation gradient- Is optimal resource partitioning theory applicable to water limited mature trees. *J. Ecol*. 1013, 29: 541 – 550.
- Hill J (1980). The remobilisation of nutrients from leaves. Journal of Plant Nutrition 2: 407 - 444.

- Hillerdal-Hagstromer K, Mattson-Djos E, and Helkvist J (1982). Field studies of water relations and photosynthesis of Scots pine. II Influence of irrigation and fertilisation on needle water potential of young pine trees. *Physiol. Plant*. 54: 295 – 301.
- Hingston FJ, Turton AG, Dimmock GM (1979). Nutrient distribution in karri (*Eucalyptus diversicolor* F.muell.) ecosystems in Southwest, Western Australia. *Forest Ecology and Management* 2: 133-158.
- Hodgson JG, Wilson PJ, Hunt R, Grime JP, Thompson K (1999). Allocating C-S-R plant functional types; a soft approach to a hard problem. *Oikos* 85: 282 – 296.
- Hoffmann A, Kummerow J (1978). Root studies in the Chilean Matorral. Oecologica 1978, 69: 57 – 69.
- Holz GK, Smethurst PJ, Pongracic S (1999). Responses to cultivation in eucalypt tree farms in southeastern Australia. In: Ellis RC, Smethurst PJ (Eds.) Practicing Forestry Today. Proceedings of the 18th Biennial Conference of the Institute of Foresters of Australia 161 – 164.
- Houghton J, Thompson K, Rees M (2013). Does seed mass drive the differences in relative growth rate between growth forms? *Proc. R. Soc. B:* 280, 20130921.
- https://en.climate-dat.org (2020) Howick Climate, South Africa. Accessed (September, 2020).
- Huang ZQ, Xu Z, Blumfield TJ and Bubb K (2008). Effects of mulching on growth, foliar photosynthetic nitrogen and water use efficiency of hardwood plantations in subtropical Australia. *Forest Ecology and Management* 255(2008): 3447-3454.
- INDUFOR, 2012. Strategic Review on the Future of Forest Plantations in the World. Study done for the Forest Stewardship Council (FSC), Bonn, Germany, pp. 1–11.
- Ingestad T (1982). Relative addition rate and external concentration; driving variables used in plant nutrition research. *Plant, Cell and Environment* 5: 443-453.
- Ingestad T, Lund AB (1986). Theory and techniques for steady state mineral nutrition and growth of plants. *Scandinavian Journal of Forest Research* 1: 439-453.
- Jacobs DF, Salifu KF, Seifert JR (2005). Relative contribution of initial root and shoot morphology in predicting field performance of hardwood seedlings, *New For*. 30 (2005) 235–251.
- Jakobsen BF, Greacen EL (1985). Compaction of sandy forest soils by forwarder operations. Soil Tillage and Research. Volume 5, Issue 1, March 1985: 55 – 70.

- Jin K, Shen J, Ashton JW, White RP, Dodd IC, Parry MAJ, Whalley WR (2015). Wheat root growth responses to horizontal stratification of fertiliser in a water limited environment. *Plant Soil* 2015, 386: 77 – 88.
- Jones HE, Dighton J (1993). The use of nutrient bioassays to assess the response of *Eucalyptus grandis* to fertiliser application. 2. A field experiment. *Canadian Journal of Forest Research* 23*:* 7-13.
- Judd TS, Attiwill PM, Adams MA (1996). Nutrient concentrations in *Eucalyptus*: a synthesis in relation to differences between taxa, sites, and components. In*:* Attiwill PM, Adams MA (Eds.) Nutrition of eucalypts*.* CSIRO Publishing, Collingwood, pp 123-154.
- Katul G, leaning R, Oren R (2003). Relationship between plant hydraulic and biochemical properties derived from a steady state coupled water and carbon transport model. *Plant, Cell & Environment* 26: 339-350.
- Kiiskila (1999). The Effect of Seedling Size on Field Performance**.** 1996-2004 Pacific Regeneration Technologies Inc. 1- 25 pp.
- Kirshbaum MUF, Tompkins D (1990). Photosynthetic responses to phosphorus nutrition in *Eucalyptus grandis* seedlings. *Australian Journal of Plant Physiology* 17: 527-535.
- Knight JH (1999). Root distributions and water uptake patterns in Eucalypts and other species. In: Landsberg JJ (Ed.). *The ways trees use water*. Barton, ACT: Rural Industries Research and Development Corporation. pp 55–85.
- Knight PJ, Nicholas ID (1996). Eucalypt nutrition: New Zealand experience. In*:* Attiwill PM, Adams MA (Eds.) Nutrition of Eucalypts*.* CSIRO Publishing, Collingwood, pp 275-302.
- Kolb PF, Robberecht R (1996). High temperature and drought stress effects on survival of *Pinus ponderosa* seedlings. *Tree Physiology* 16: 665 – 672.
- Kozlowski TT (1972). Water deficits and Plants, Volume III. Plant Response and Control of Water Balance. Academic Press, New York.
- Kozlowski TT, Davies WJ (1975). Control of water balance in transplanted transplants. Arboriculture 1: 1-10*.*
- Kramer PJ, (1969). Plant and soil water relationships: a modern synthesis. McGraw-Hill Book Company, New York.
- Kriedemann PE, Cromer RN (1996). Nutritional physiology of eucalypts: nutrition and growth. In*:* Attiwill PM, Adams MA (Eds.) Nutrition of eucalypts*.* CSIRO Publishing, Collingwood, pp 109 -121.

- Lacey CJ, Leaf AL, Talli AR (1966). Growth and nutrient uptake by flooded gum seedlings subjected to various phosphorus supplies. *Australian Forestry* 30: 212 - 222.
- Laclau JP (2001). Dynamique du fonctionnement mineral d'une plantation *d'Eucalyptus*. Efffets du reboisement sure en sol de savane du littoral congolais conséquences pour le gestion des plantations industrielles. D.Sc. Thesis. Institut National Agromoique. Paris-Grignon, Paris, France, 148 pp.
- Lamb D (1976). Variations in the foliar concentrations of macro- and micro-elements in a fast growing tropical eucalypt. *Plant and Soil* 45: 477 - 492.
- Lamb D (1977). Relationships between growth and foliar nutrient concentrations in *Eucalyptus deglupta*. *Plant and Soil* 47: 495 - 508.
- Lambert MJ (1981a). Inorganic constituents in wood and bark of New South Wales forest tree species. Forestry Commission of New South Wales, Research note No. 24. Sydney, New South Wales.
- Lambert MJ (1981b). Inorganic constituents in wood and bark of New South Wales forest tree species. Forest Commission of New South Wales, Research note No. 45. Sydney, New South Wales. 42 pp.
- Lamhamedi MS, Lambany G, Margolis H, Renaud M, Veilleux L, Bernier PY (2001). Growth, physiology, root architecture and leaching of air-slit containerized *Picea glauca* seedlings (1+0) in response to time domain reflectometry control irrigation regime, *Can. J. For. Res*. 31 (2001) 1968–1980.
- Landis TD, Van Wordragen MF (2006). Seedling quality testing at the gene level. In: Dumroese RK (ed.) Forest Nursery Notes. Summer 2006. USDA Forest Service. Pacific Northwest Region. pp 4 – 5.
- Larcher W, (1987). Streβ bei Pflanzen. (Stress in plants.) Naturwissenschaften 74:158 -167.
- Larcher W, Wagner J, Thammathaworn A (1990). Effects of superimposed temperature stress on in vivo chlorophyll fluorescence of *Vigna unguiculata* under saline stress. *Journal of Plant Physiology* 136:92-102.
- Larocque, GR, Marshall PL (1993). Evaluating the impact of competition using relative growth rate in red pine (Pinus resinosa) Ait.) stands. *For. Ecol. Manag*. 58: 65-83.
- Leon MF, Squeo FA, Gutierrez JR, Holmgren M (2011). Rapid root extension during water pulses enhances establishment of shrub seedlings in the Atacama Desert, *J. Veg. Sci*. 22: 120 -129.

- Leuning R, Cromer RN, Rance S (1991). Spatial distribution of foliar nitrogen and phosphorus in crowns of *Eucalyptus grandis* canopies. *Oecologia* 88: 504 - 510.
- Levitt J, (1972). Responses of Plants to Environmental Stresses. Academic Press, New York and London. 697 pp.
- Levitt J, (1980). Responses of Plants to Environmental Stresses. Second Edition, Vols. I and II. Academic Press, New York and London. Ed. 2. 607 pp.
- Li Th, Li Sh (2005). Leaf responses of micropropagated apple plants to water stress: non-structural carbohydrate composition and regulatory role of metabolic enzymes. *Tree Physiology* 25: 495 - 504.
- Linder S, (1982). The importance of controlled plant nutrient status in comparative studies of tree seedlings. In: Puutonen P (ed.) Vitality and Quality of Nursery Stock. Univ. Helsinki, Dept. Silviculture, Research Note 36, pp 75 - 84.
- Little KM (2014). Interpreting the growth of trees in response to site, species or silvicultural treatment. Tsitsikamma Silviculture Field Day - 18 September 2014. ICFR, Pietermaritzburg.
- Little KM, Eccles N, Oscroft D, Viero P, Eastwood T (1996). Growth of eucalypts on slash managed and burned sites in Zululand. ICFR Bulletin Series 3/96, Institute for Commercial Forestry research, Pietermaritzburg. PP 37.
- Little, KM, Rolando, CA (2002). Post-establishment vegetation control in a *Eucalyptus grandis* x *E. camaldulensis* stand. *S. Afr. For. J*. 193, 77–80.
- Lloret F, Siscart D, Dalmeses C (2004). Canopy recovery after drought dieback in holm-oak Mediterranean forests of Catalonia (NE Spain) Global Change Biology 10: 2092 - 2099.
- Loneragan JF, Snowball K, Robson AD (1976). Remobilisation of nutrients and its significance in plant nutrition. In: Wardlaw IF, Passioura JB (Eds.) Transport and transfer processes in plants. Academic Press, London, pp 463-469.
- MacLennan L, Fennessy J (2006). Plant quality - A key to success in forest establishment. In: Proceedings of the COFORD conference, 20-21 September 2005, Mount Wolseley Hotel, Tullow, Co Carlow. Council for Forest Research and Development, Dublin. pp. 11-61.
- Maclennan L, Fennessy J (2006). Plant quality - A key to success in forest establishment. In: *Proceedings of the COFORD conference, 20-21 September 2005,*

Mount Wolseley Hotel, Tullow, Co Carlow. Council for Forest Research and Development, Dublin. pp. 11-61.

- MacVicar CN, De Villiers JM (conveners) (1991). Soil Classification A Taxonomic System For South Africa, Memoirs on the Agricultural Natural Resources of South Africa No. 15. Department of Agricultural Development, Pretoria.
- MacVicar CN, De Villiers JM, Loxton RF, Verster E, Lambrechts JJN, Merryweather FR, Le Roux J, Van Rooyen TH, Von M. Harmse HJ (1988). 3rd reprint. Soil Classification: A Binomial System For South Africa. The Department of Agricultural Technical Services Republic of South Africa. Science Bulletin 390, Pretoria.
- Madeira MV, Fabião A, Pereira JS, Araújo MC, Ribeiro C (2002). Changes in carbon water stocks in *Eucalyptus globulus* Labill. Plantations induced by different water and nutrient availability. *Forest. Ecology Management*. 171 (1 – 2), 75 – 78.
- Maggs J (1985). Litter fall and retranslocation of nutrients in a refertilised and prescribed burned *Pinus elliottii* plantation. *Forest Ecology and Management* 12: 53 - 268.
- Maherali H, De Lucia EH (2001). Influence of climate-driven shifts in biomass allocation on water transport and storage in ponderosa pine. *Oecologica* 129: 481 - 491.
- Malan FS (1993). The wood properties and qualities of three South African-grown *Eucalyptus* hybrids. *South African Forestry Journal* 146: 38-43.
- Manion PD (1991). Tree disease concepts. Upper Saddle River, NJ, USA: Prentice Hall. Ed. 2. 402 pp.
- Margolis HA and Brand DG (1990). An ecophysiological basis for understanding plantation establishment. *Can. J. For. Res*. 20: 375 – 390.
- Marschner H (1999). Mineral Nutrition of Higher Plants. 2nd edition. Academic Press, London, pp 228 - 435.
- Mattsson A (1997). Predicting field performance using seedling quality assessment. *New Forests* 13: 227 - 252.
- McCubbin PD and Smith IE (1991). The influence of four seedling tray types over time on root growth and other growth parameters of *Eucalyptus grandis* seedlings, pp 143 - 155. In: Schönau APG (Ed.) Proceedings of Symposium on Intensive Forestry: The Role of Eucalypts, Vol. 1.
- McDowell N, Pockman WT, Allen CD, Breshears DD, Cobb N, Kolb T, Plaut J, Sperry J, West A, Williams DG and Yepez EA (2008). Mechanisms of plant survival and

mortality during drought: why do some plants survive whilst others succumb to drought? *New Phytologist* (2008) 178:719 - 739.

- McDowell NG, Phillips N, Lunch CK, Bond BJ, Ryan MG (2002). Hydraulic limitation and compensation in large old Douglas–fir trees. *Tree Physiology* 22: 763.
- McGill WB and Christie EK (1983). Biogeochemical aspects of nutrient cycle interactions in soils and organisms. In: Bolin B and Cook RB (Eds.). The Major Biogeochemical Cycles and their Interactions. Wiley, New York pp. 271 – 301.
- Mead DJ (2005). Opportunities for improving plantation productivity. How much? How quickly? How realistic? *Biomass and Bioenergy* 28: 249–266.
- Medina E (1983). Adaptation of tropical trees to moisture stress. In: Golley FB (Ed) Tropical rain forest ecosystems. Structure and function. Elsevier Scientific Publishing Company, Amsterdam. 225 – 227 pp.
- Mello SLM, Gonçalves JLM, Oliveira LEG (1998). Características do sistema radicular em povoamentos de eucaliptos propagados por sementes e estacas. *Scientia Forestalis* 54: 17–28.
- Mencuccini M, Bonosi L (2001). Leaf/sapwood ratios in Scots pine show acclimation across Europe. *Canadian Journal of Forests Research* 31: 442 – 456.
- Mengel K and Kirby EA (1982). Principles of Plant Nutrition. International Potash Institute, Bern.
- Miller, HG (1995). The influence of stand development on nutrient demand, growth and allocation. *Plant and soil* 177: 168-169, 225-232.
- Misra RK and Gibbons (1996). Growth and morphology of eucalypt seedling roots in relation to soil strength arising from compaction. *Plant Soil* 182: 1 – 11.
- Mitchell PJ, O'Grady AP, Tissue DT, White DA, Ottenschlaeger ML, Pinkard EA (2013b). Drought response strategies refine the relative contribution of hydraulic dysfunction and carbohydrate depletion during tree mortality. *New Phytol*. 197(3), 862 – 872.
- Mitton JB (1995). Genetics and the physiology ecology of conifers. In: Smith WK, Hinckley TM (Eds.) Ecophysiology of coniferous forests. San Diego, Ca, USA: Academic Press, 1-36.
- Mondi GIS Department (2009). Mondi SA, Hilton, KZN.

- Morris A, (1994). Trial series R172 Final Report: Seedling Quality and Late Season Planting of *Pinus patula*. Forest Research Document 16/93, Usutu Pulp Company. Swaziland. 11 pp.
- Morris, AR (1986). Soil fertility and long-term productivity of *Pinus patula* in Swaziland. PhD Thesis, University of Reading, U.K. 388 pp.
- Morris AR (1993). Forest floor accumulation under *Pinus patula* in the Usutu forest, Swaziland. *Commonwealth Forestry Review* 72: 114-117.
- Morris AR (1994). Factors influencing post-planting survival in late season re-establishment of *Pinus patula*. *Forest research Document* No. 16/94. 6 pp.
- Morris J, Zhang NN, Yang ZJ, Collopy J, Xu DP (2004). Water use by fast growing *Eucalyptus urophylla* plantations in Southern China. *Tree Physiology* 24: 1035 – 1044.
- Morris AR. 2008. Realising the benefit of research in eucalypt plantation management. *Southern Forests* 70: 119–129.
- Mucina L and Rutherford MC (2006). National Vegetation Types of South Africa, Lesotho and Swaziland. South African National Biodiversity Institute. Pretoria, 801 pp.
- Mulligan DR (1988). Phosphorus concentrations and chemical fractions in *Eucalyptus* seedlings grown under nutrient deficient conditions. *New Phytologist* 110: 479-486.
- Mulligan DR, Patrick JW (1985). Phosphorus and carbon economies of ectomycorrhizal seedlings of *E. pilularis* SMITH. *Australian Journal of Plant Physiology* 12: 669-679.
- Murphy PA, Shelton MG (1996). An individual-tree basal area growth model for loblolly pine stands. *Canadian Journal Forestry Research* 26: 327-337.
- Myers BJ, (1988). Water stress integral – a link bettween short-term stress and long term growth. *Tree Physiology* 4: 315 – 323.
- Myers BJ, Landsberg JJ (1989). Water stress and seedling growth of two eucalypt species from contrasting habitats. *Tree Physiology* 5: 207-218.
- Nambiar EKS and Sands R (1993). Competition for water and nutrients in forests. *Canadian Journal Forestry Research* 23: 1955 – 1968.
- Nambiar EKS, Bowen GD, Sands R (1979). Root regeneration and plant water stress of *Pinus radiata* D. Don transplants transplanted to different soil temperatures. *Journal of Experimental Botany* 30(119): 1119-1131.
- Nambiar EKS, Squire RO, Sands R, Will GM (1984). Manipulation of water and nutrients in plantations off fast growing species. In: Grey DC, Schönau APG, Schutz CJ, (Eds.)

Proceedings of the IUFRO Symposium on Site Productivity of Fast Growing Plantations. Pretoria and Pietermaritzburg, South Africa 489 – 506.

- National Water Act 36 of 1998 (1998). South Africa. 211 pp.
- Neary DG, Rockwood DL, Comerford NB, Swindel BF, Cooksey TE (1990). Importance of weed control, fertilisation, irrigation and genetics in harvest residue and loblolly pine early growth on poorly drained podosols. *Forest Ecology and Management* 30: 271-281. 88.
- Negi JDS, Sharma SC (1996). Mineral nutrition and resource conservation in India. In: Attiwill PM, Adams MA (Eds.) Nutrition of eucalypts. CSIRO Publishing, Collingwood, pp 399-416.
- Nielsen E, Orcutt D (1996). The physiology of plants under stress. Abiotic factors, J. Wiley & Sons, New York, 1996. 801 pp.
- Nouvellon Y, Stape JL, Le Maire G, Epron D, Gonçalves JLM, Bonnefond JM, Campoe O, Loos R, Bouillet JP, Laclau JP. 2011. Factors controlling carbon and water balances on fast growing Eucalyptus plantations. In: Plinio S (ed.), *Joining silvicultural and genetic strategies to minimize* Eucalyptus *environmental stress: from research to practice*. Porto Seguro: ESALQ. pp 43–46.
- O'Connell A V, Grove TS, Dimmock G M (1978). Nutrients in the litter on jarrah forest soils. *Australian Journal of Ecology* 3: 253-260.
- Olsen JK, Bell LC (1990). A glasshouse evaluation of the 'critical' N and P concentrations and N: P ratios in various plant parts of six eucalypt species. *Australian Journal of Botany* 38: 281-298.
- Opti-Science (2005). CCM-200 Chlorophyll Content Meter. Opt-Sciences, Inc. 8 Winn Avenue, Hudson, New Hampshire 03051, USA. www.optisci.com.
- Otto MSG (2015). Physiological responses of forest species to water stress. PhD thesis, University of São Paulo, Piracicaba, Brazil.
- Ovalle JF, Arellano EC, Ginocchio R (2015). Trade-offs between drought survival and rooting strategy of two South American Mediterranean tree species: Implications for dryland forest restoration. *Forests* 6: 3733 – 3747.
- Padilla F, Miranda JDD, Armas C, Pugnaire F (2015). Effects of changes in rainfall amount and pattern on root dynamics in an arid shrubland. *J. Arid Environ*. 114: 49 – 53.
- Paiva HN and Gomes JM (1993). Viveiros florestais. Viçosa MG: UFV 56 pp.

- Pallett RN, Sale G (2002). Operational gain: measuring the capture of genetic gain. *Southern African Forestry Journal* 195: 33–38.
- Papadopol CS, (2005). Determination of Soil Hydraulic Conductivity in Nurseries and Plantations. In: ROSE R (Ed) Tree Planters' Notes. U.S. Department of Agriculture – *Forest Service* 51 (1): 22-26.
- Passioura JB (1986). Resistance to drought and salinity: avenues of improvement. *Australian Journal Plant Physiology*. 13:191-201.
- Pederson BS (1998). The role of stress in the mortality of Midwestern oaks as indicated by growth prior to death. *Ecology* 79: 79 – 93.
- Pereira AR, Angelocci LR, Sentelhas (2007) Meterologica Agricola (Ediçiao revista e amplida). Universidad de Sao Paulo, Escola Superior de Agricultura "Luis de Queiroz", Departamento de Ciências Exatas, Piracicaba, SP, 184 pp.
- Pereira JS, Tomé M, Madeira M, Oliveira AC, Tomé J, Almeida MH (1996). Eucalypt plantations in Portugal. In: Attiwill PM, Adams MA (Eds.) Nutrition of eucalypts. CSIRO Publishing, Collingwood, pp 371 - 387.
- Pinheiro RC, de Deus JC, Nouvellon Y, Campoe OC, Stape JL, Aló LL, Guerrini IA, Jourdan C, Laclau JP (2016). A fast exploration of very deep soil layers by *Eucalyptus* seedlings and clones in Brazil. *Forest Ecol. Manage*., 366, 143–152.
- Pita P, Pardos JA (2001). Growth, morphology, water use and tissue water relations of *Eucalyptus globulus* clones in response to water deficit, *Tree Physiol*. 2: 599–607.
- Pittermann J, Sperry JS, Hacke UG, Wheeler JK, Sikkema EH (2006). Inter-tracheid pitting and the hydraulic efficiency of conifer wood: the role of tracheid allometry and cavitation protection. *American Journal of Botany* 93: 1105 – 1113.
- Pommerening A, Muszta A (2016). Relative plant growth revisited: Towards a mathematical standardisation of separate approaches. *Ecological modelling* 320 (2016) 383 -392.
- Prenger JJ and Ling PP (2015). Greenhouse condensation control: Understanding and using vapour pressure deficit (VPD). Ohio State University: Extension Fact Sheet. AEX-804: 1- 4.
- Prescott CE (2002). The influence of the forest canopy on nutrient cycling of *Eucalyptus* plantations. *Tree Physiology* 22 1192-1200.

- Prescott CE, Vesterdal L, Pratt J, Venner KH, De Montigny LM and Trofymow, JA (2000*c*). Nutrient concentrations and nitrogen mineralization in forest floors of single species conifer plantations in coastal British Columbia. *Can. J. For. Res*. 30:1341-1352.
- Puttonen P. (1986). Carbohydrate reserves in *Pinus sylvestris* seedling needles as an attribute of seedling vigor. *Scand. J. For. Res.* 12:905-912.
- Reganold JP, Harsh JB (1985). Expressing cation exchange capacity in milliequivalents per 100 grams and in SI units[1].) *Journal of Agronomic Education*, Vol. 14, No. 2, Fall 1985.
- Reis ER (2008). Período de permanência de mudas de *Eucalyptus grandis* em viveiro baseado em parâmetros morfológicas. Revista Árvore, Viçosa vol 3 no.5 809-814.
- Richie GA (2003). Root physiology and phenology: the key to transplanting success. Available at http://www.fcnanet.org/proceedings/2002/richie.pdf [accessed 15 March 2018].
- Ritchie GA and Landis TD (2003). Seedling Quality Tests: Root Growth Potential. Forest Nursery Notes United States Department of Agriculture (Winter 2003) 8-10.
- Rocha JHT, du Toit B, Goncalves JLM (2019). Ca and Mg nutrition and its application in *Eucalyptus* and *Pinus* plantations. *Forest Ecology and Management* 442: 63–78.
- Rolando CA (2008). The physiology of *Pinus patula* seedlings in response to water stress and the implications for plantation regeneration in South Africa. Published PhD thesis, University of KwaZulu-Natal, South Africa, 148 pp.
- Rolando CA, Little KM (2004). Measuring the effects of water stress on *Pinus patula* seedlings transplanted into pots: A pilot investigation. Pietermaritzburg, Institute for Commercial Forestry Research.
- Rolando CA, Little KM (2005). Results of a pot trial measuring water stress on *Eucalyptus grandis* seedlings. Pietermaritzburg, Institute for Commercial Forestry Research, pages.
- Rolando CA, Little KM (2008). Measuring water stress in *Eucalyptus grandis* Hill ex Maiden seedlings planted into pots. South African *Journal of Botany* 74 (2008): 133 - 138.
- Rolando CA, Little KM (2009). The effect of plant size, planting depth and planting method on three-year *Pinus patula* survival and growth in South Africa. *ICFR Bulletin Series* No. 15/2009. Pietermaritzburg: Institute for Commercial Forestry Research.

- Rolando CA, Little KM, Norris CH (2002). Final results of the first rotation of a residue management trial in Zululand. ICFR Bulletin 04/2002. Pietermaritzburg, Institute for Commercial Forestry Research.
- Romme WH, Clement J, Hicke J, Kulakowski D, MacDonald LH, Schonnagel TL, Veblen TT (2006). Recent forest insect outbreaks and fire risk in Colorado forests: a brief synthesis of recent research. Colorado Research Institute, Colorado, 24 pp.
- Royo A, Fernandez M, Gil L, Pardos JA (2003). Assessing the hardiness of Aleppo Pine, Maritime Pines, and Holm Oak seedlings by electrolyte leakage and water potential methods. In: Hernandez, (ed.) Tree Planters' Notes 50 (1) 38-43.
- Ryan MG, Binkley D, Fownes JH (1997). Age related decline in forest productivity: pattern and process. *Adv. Ecol. Res*. 27, 213 – 262.
- Salau OA, Oparanadi OA, Swennen R (1992). Effects of mulching on soil properties, growth and yield of plantain on a tropical utisol in Southeastern Nigeria. *Soil Tillage Research* 23: 73-93.
- Sands R (1984). Transplanting stress in *radiata* pine. *Australian Forest Research* 14: 67-72.
- Sasse J, Sands R, (1996). Comparative responses of cuttings and seedlings of *Eucalyptus globulus* to water stress, *Tree Physiol*. 16: 287–294.
- Scholander PF, Hammel HT, Bradstreet ED and Hemmingsen EA (1965). Sap pressure in vascular plants. Science 148:339 – 346.
- Schönau APG (1981). Seasonal changes in foliar nutrient content of *Eucalyptus grandis. South African Forestry Journal* 119:1-4.
- Schönau APG (1983). Fertilization in South African Forestry. *South African Forestry Journal* 125: 1-19.
- Schönau APG (1989) Requirements for intensive silviculture. *South African Forestry Journal* 150: 40–48.
- Schönau APG, Herbert MA (1983). Relationships between growth rates, fertilizing and foliar nutrient concentration for *Eucalyptus grandis*; preliminary investigations. Fertilizer Research 4: 369-380.
- Schönau APG, Herbert MA (1989). Fertilizing eucalypts at plantation establishment. *Forest Ecology and Management* 29*:* 221-244
- Searson MJ, Thomas DJ, Montagu KD, Conroy JP (2004). Leaf water use efficiency differs between *Eucalyptus* seedlings from contrasting rainfall environments. *Funct. Plant Bio*; 31: 441 – 450

- Sheriff DW, Nambiar EKS (1991). Nitrogen nutrition, growth and gas exchange in *Eucalyptus globulus* Labill. seedlings. *Australian Journal of Plant Physiology* 18: 37-52.
- Silva CR, Gonçalves JLM, Folegatti BS, Stape JL and Gava JL (1997). Weed proliferation in eucalypt stands established under minimum and intensive site preparation. In: Proceedings of the IUFRO conference on silviculture and improvement of eucalypts, 24 – 29 August 1997, Salvador, Brazil, vol. 3 Embrapa, Colombo, Brazil. 234 – 241.
- Slayter RO (1957). Significance of the permanent wilting percentages in studies of plants and soil water relations. *Bot. Rev*. 23: 585.
- Slayter RO (1967). Plant-Water relationships. Academic Press, London, 366 pp.
- Smethurst PJ, Baillie C, Cherry M, Holz G (2003). Fertilizer effects on LAI and growth of four Eucalyptus nitens plantations. *For. Ecol. Manage*. 176: 531 – 542.
- Smethurst PJ, Wang BG (1998). Soil solution phosphorous and Eucalyptus nitens roots in NP-treated microsites in highly phosphorus fixing soil. *New Zealand Journal Forestry Science*: 28:140 – 51.
- Smith CW, Du Toit B (2005). The effect of harvesting operations, slash management and fertilisation on the growth of a eucalyptus clonal hybrid on a sandy soil. *Southern African Forestry Journal*, 203.
- Smith FW, Loneragan JF (1997). Interpretation of plant analysis: concepts and principles. In: Reuter DJ, Robinson (Eds.) Plant analysis an interpretation manual. 2nd edition. CSIRO Publishing, Collingwood, pp 3-33.
- Smith, CW, Pallett, RN, Kunz, R.P. and Gardner, RW (2005). A strategic forestry site classification for the summer rainfall region of southern Africa based on climate, geology and soils. *ICFR Bulletin Series* 03/2005, Institute for Commercial Forestry Research, Pietermaritzburg.
- South DB, Harris SW, Barnett JP, Hainds MJ and Gjerstad DH (2004). Effect of container type and seedling size on survival and early height growth of *Pinus palustris* seedlings in Alabama, *U.S. Forest Ecology and Management* 204:2 (2004) 385-398.
- South DB, Mitchell RG (2006). A root-bound index for evaluating plants quality of container-grown pines. *Southern African Forestry Journal* 207(1): 47-54.
- Souza AJ, (2002). Preparo de solos coesos para cultura do eucalipto no extreme sul do Bahia. In: Gonçalves JLM and Stape JL (Eds.) Conservação e cultivo de solos para plantações florestais. Instituto de Pesquisas e Estudos Florestais, Piracicaba. 259-296.

- Specht RL, Groves RH (1996). A comparison of the phosphorus nutrition of Australian heath plants and introduced economic plants. *Australian Journal of Botany* 14: 201-221.
- Sperry JS, Adler FR, Campbell GS, Comstock JP (1998). Limitation of plant water use by the rhizosphere and xylem conductance results from a model. *Plant, Cell & Environment* 21: 347-359.
- Sperry JS, Hacke UG, Oren R, Comstock JP (2002). Water deficits and hydraulic limits to leaf water supply. Plant, Cell & Environment 25: 251 – 263.
- Squire RO (1977). Interacting effects of grass competition, fertilising and cultivation on the early growth of *Pinus radiata* D. Don. *Australian Forest Research* 7: 247-252.
- Stape JL, Andrade S, Gomes AN, Krejci LC, Ribeiro JA (2002). Definição de métodos de preparo de solo para silvicultura em solos coesos do litoral norte da Bahia. In: Gonçalves JLM, Stape JL (Eds), *Conservação e cultivo de solos para plantações florestais*. Piracicaba: IPEF. pp 259–296.
- Stape JL, Binkley D, Ryan MG (2004). *Eucalyptus* production and the supply, use and efficiency of use of water, light and nitrogen across a geographic gradient in Brazil. *Forest Ecology and Management* 193: 17–31.
- Stape JL, Binkley D, Ryan MG (2008). Production and carbon allocation in a clonal *Eucalyptus* plantation with water and nutrient manipulations. *Forest Ecology and Management* 255: 920–930.
- Stape JL, Goncalves JLM, Goncalves AN (2001). Relationships between nursery practices and field performance for *Eucalyptus* plantations in Brazil. *New For* 22:19–41.
- Stewart JD, Lieffers VJ (1993). Preconditioning effects of nitrogen addition rate and drought stress on container-grown lodge pole seedlings, Can. J. For. Res. 23: 1663–1671.
- Stoneman GL, Crombie DS, Whitford K, Hingston FJ, Giles R, Portlock CC, Galbraith JH, Dimmock GM (1996). Growth and water relations of *Eucalyptus marginata* (jarrah) stands in response to thinning and fertilization. *Tree Physiology* 16: 267–274.
- Strahler AN, Strahler AH (1987). Modern Physical Geography, Third edition. John Wiley and Sons. New York. 106 - 107.
- Sun OJ, Sweet GB, Davis M (2001). Comparative mineral nutrition of *Nothofagus solandri* var. *cliffortioides* and *N. menziesii* seedlings. *New Zealand Journal of Forestry Science* 31: 157-169.

- Sutton RF (1979). Planting stock quality and grading. *Forest Ecology and Management* 2: 123–132.
- Tear EC, Higginbotham KO, Mayo JM (1982). Effects of drying soils on survival of young *Picea glauca* transplants. *Canadian Journal of Forestry Research* 12: 1005-1009.
- Tenhunen JP, Lange OL and Pearcy RW (1987). Diurnal variations in leaf conductance and gas exchange in natural environments. In Zeiger E, Farquar GD and Cowan IR (Eds.) Stomatal Function. Stanford University Press, Stanford 323 – 351.
- Theron K (2000). Site requirements and species matching. South African Forestry Handbook 2000. Vol. 1. The Southern African Institute of Forestry, Pretoria, 400 pp.
- Thomas DS (2008). Hydrogel applied to the root plug of subtropical eucalypt transplants halves transplant death following planting. *Forest Ecology Management* 255:1305–1314.
- Thornthwaite CW (1948). An approach toward a Rational Classification of Climate. Geographical Review, Vol. 38, No.1. 55 - 94.
- Thomas DS (1990). Survival and growth of drought hardened *Eucalyptus pilularis* Sm. seedlings and vegetative cuttings. *New Forests* (2009) 38:245–259.
- Titshall L, Dovey S, Reitz D (2013). A review of management impacts on the soil productivity of South African commercial forestry plantations and the implications for multiple-rotation productivity. *Southern Forests*: 75: - Issue 4.
- Tuberosa R, Salvi S, Sanguineti MC, Maccaferri M, Giuliani S, Landi P (2003). Searching for quantitative trait loci controlling root traits in maize: a critical appraisal. *Plant and Soil* 255: 35 – 54.
- Turner J, Lambert MJ (1983). Nutrient cycling within a 27-year-old *Eucalyptus grandis* plantation in New South Wales. *Forest Ecology and Management* 6:155-168.
- Turner J, Lambert MJ (1986) Nutrition and nutritional relationships in *Pinus radiata*. *Annual Rev. Ecol. Syst.* 17: 325-350.
- Turner NC, Waggoner PE (1969). Effects of changing stomatal width in a red pine forest on soil water content, leaf water potential, bole diameter and growth. Plant Physiol. 43, 973.
- Turvey ND (1996). Growth at age 30 months of *Acacia* and *Eucalyptus* spp. planted in *Imperata* grasslands in Kalimantan Selata, Indonesia. *Forest Ecology and Management* 82: 185-195.

- Tutua SS, Xu ZH, Blumfield TJ and Bubb KA (2008). Long-term impacts of harvest residue management on nutrition, growth and productivity of an exotic pine plantation of sub-tropical Australia. *Forest Ecology and Management* 256(2008): 741 - 748.
- Tyree MT, Jarvis P (1982). Water tissue and cells, in: Lange OL, Nobel PL, Osmond CB, Ziegler H. (Eds.), Encyclopedia of plant physiology, NS, *Physiological plant ecology* II, Vol. 12B, Springer, Berlin Heidelberg, New York, pp. 37–77.
- Tyree MT, Sperry JS (1988). Do woody plants operate near the point of catastrophic xylem dysfunction caused by dynamic water stress? *Plant Physiology* 88: 574 – 580.
- Valdecantos A, Fuentes D, Smanis A, Llovet J, Morcillo L, Bautista S (2014). Effectiveness of low-cost planting techniques for improving water availability to *Olea europaea* saplings planted in degraded drylands. *Resto. Ecol* 2014, 22: 327 – 335.
- Vale FR, Novais RF, Barros NF, Sant'anna R (1984). Efeito do alumínio sobre a cinética da absorção de amônio e nitrato em raízees intactas de *Eucalyptus alba. Revista Árvore* 8*:* 123 - 132.
- Van den Driessche R (1991). Influence of container nursery regimes on drought resistance of seedlings following planting. I. Survival and growth, *Can. J. For. Res*. 21: 555–565.
- Vance ED, Maguire DA, Zalesny RS Jr. (2010). Research strategies for increasing productivity of intensively managed forest plantations. *Journal of Forestry*, June 2010: 183 – 192.
- Viero PWM (2004). Eucalypt establishment and re-establishment research conducted by the ICFR, South Africa. *ICFR Bulletin Series* No.09/2004(9). Pietermaritzburg: Institute for Commercial Forestry Research.
- Viero PWM (2019). Literature review on plant quality research with reference to eucalypt re-establishment in RSA. Operational Excellence Technical Note, Mondi SA, Hilton, 5 pp.
- Villa-Salvador P, Planelles R, Oliet J, Penuelas-Rubira JL, Jacobs DF Gonzales M (2004). Drought tolerance and transplanting performance of Holm oak (*Quercus ilex*) seedlings after drought hardening in the nursery. *Tree Physiology* 24: 1147 – 1155.
- Wallace IM, Dell B, Loneragan JF (1986). Zinc nutrition of jarrah (*Eucalyptus marginata* Donn ex Sm.) seedlings. *Australian Journal of Botany* 34: 41-51.
- Wang D, Bachelard EP, Banks CG (1988). Growth and water relations of two subspecies of *Eucalyptus globulus*, *Tree Physiol*. 4: 129–138.

- Wendling I, Paiva HN, Gonçalvez W (2005). Técnicas de produção de mudas de plantas ornamentais. Viçosa. MG: Aprenda Fácil v. 3, 203 pp.
- Wenk G, Antanaitis V, Smelko S (1990). Waldertragslehre [Forest Growth and Yield Science]. Deutscher Landwirtschaftsverlag, Berlin, 448 pp.
- Weston CJ, Attiwill PM, Cameron JN (1991). Growth and nutrition of eucalypts in relation to soil type and former land use in Gippsland, Victoria. In: Schönau APG. (Ed), Intensive Forestry: The role of Eucalypt. IUFRO Symposium. South African Institute of Forestry, Durban, 480 – 491.
- Whitehead D, Beadle CL (2004). Physiological regulation of productivity and water use in *Eucalyptus*: a review. *For. Ecol. Manage*. 193: 113 – 140.
- Whyte G, Howard K, Hardy GE St.J. Burgess TI (2016). The Tree Decline Recovery Seesaw; a conceptual model of the decline and recovery of drought stressed plantations trees. *Forest Ecology and Management* 370: 102 – 113.
- Will GM (1985). Nutrient deficiencies and fertilizer use in New Zealand exotic forests. FRI Bulletin No. 97, Forest Research Institute, Rotorua, pages.
- Wilson PJ, Thompson K, Hodgson JG (1999). Specific leaf area and leaf dry matter content as alternative predictors of plant strategies. *New Phytol*. (1999), 143, 155 -162
- Woodwell GM (1974). Variation in the nutrient content of leaves of *Quercus alba, Quercus coccinea* and *Pinus rigida* in the Brookhaven forest from bud break to abscission. *American Journal of Botany* 61: 749-753.
- Xu D and Dell B (2002). Nutrient management for eucalypt plantations in South China. *Chinese Forestry Science and Technology* 1: 1 - 9.
- Zwiazek JJ, Blake TJ (1989). Effects of preconditioning on subsequent water relations, stomatal sensitivity, and photosynthesis in osmotically stressed black spruce, Can. J. Bot. 67: 2240–2244.
- Zwolinski JB and Bayley AD (2001). Research on planting stock and forest regeneration in South Africa. *New Forests* 22 (2001) 59-74.
- Zwolinski JB, Donald DGM, Van Laar A and Groenewald W (1994). Regeneration procedures of *Pinus radiata* in the Southern Cape Province. Part V: Post–planting mortality and growth of trees in response to the experimental treatments and planting site environment. *South African Forestry Journal* 168:7 - 21.

- Zwolinski JB, South DB, Cunningham L, Christie SI (1995). Weed control and large planting stock improve survival and early growth of *Pinus radiata*. *New Zealand Forest Research Bulletin* No. 192. Rotorua, New Zealand, pp. 182-184.